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(71) Applicant *(for all designated States except US)*: **NEW-SOUTH INNOVATIONS PTY LIMITED** [AU/AU]; Rupert Myers Building, Gate 14, Barker Street, Sydney, New South Wales 2052 (AU).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **TRUPKE, Thorsten** [DE/AU]; 327 Arden Street, Coogee, NSW 2034 (AU). **BARDOS, Robert, Andrew** [AU/AU]; 2/36 Dickson Street, Bronte, NSW 2024 (AU).

(74) Agent: **SPRUSON & FERGUSON**; GPO Box 3898, Sydney, NSW 2001 (AU).

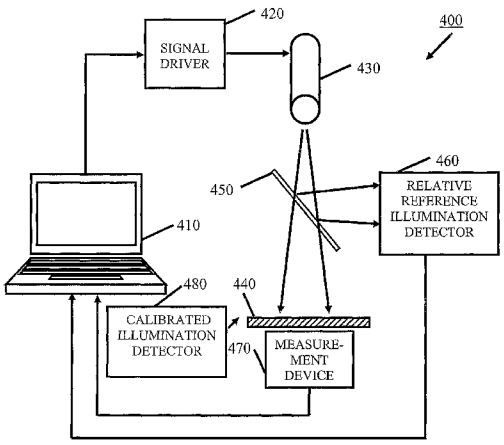
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(54) **Title:** METHODS AND SYSTEMS OF PRODUCING SELF-CONSISTENTLY A CALIBRATION CONSTANT FOR EXCESS CHARGE CARRIER LIFETIME



(57) **Abstract:** Methods (500) and systems (400, 800, 900) for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample (440, 840, 940) are disclosed. In one method, the sample (440, 840, 940) is reproducibly illuminated (512) with time-varying absolute photon flux, and a physical response of the sample (440, 840, 940) dependent on the excess charge carrier density is contactlessly measured (518). The calibration factor is self consistently produced (520) dependent upon a charge carrier generation rate per unit volume as a function of time, and the measured physical response of the sample (440, 840, 940). The charge carrier generation rate may be known by measuring (616, 618, 619) absolute photon flux incident upon the sample (440, 840, 940). In another method, the sample (440, 840, 940) is illuminated with time-varying absolute photon flux. The photon flux incident upon the sample (440, 840, 940) is measured (514). Self consistently producing the calibration factor is dependent upon the reference illumination measurement, physical properties of the sample (440, 840, 940), and the measured physical response of the sample (440, 840, 940).

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METHODS AND SYSTEMS OF PRODUCING SELF-CONSISTENTLY A CALIBRATIO CONSTANT FOR EXCESS CHARGE CARRIER LIFETIME

TECHNICAL FIELD

The present invention relates generally to semiconductors and more particularly to methods of determining excess charge carrier lifetime in semiconductor structures.

SUMMARY

In accordance with an aspect of the invention, there is provided a system for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample. The system comprises: a light source for reproducibly illuminating a semiconductor sample with a time-varying absolute photon flux; a measurement device for contactlessly measuring a physical response of the semiconductor sample dependent on the excess charge carrier density in the semiconductor sample produced by the illumination; and a processor coupled to the measurement device for producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of the semiconductor sample dependent upon a charge carrier generation rate per unit volume as a function of time, and the measured physical response of the semiconductor sample.

The charge carrier generation rate is known by measuring the absolute photon flux as a function of time incident upon the semiconductor sample and is dependent upon known physical properties of said semiconductor sample.

In accordance with another aspect of the invention, there is provided a system for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample. The system comprises: a light source for illuminating a semiconductor sample with a time-varying absolute photon flux; a reference illumination detector to measure the photon flux incident upon the semiconductor sample emitted by the light source; a measurement device for contactlessly measuring a physical response of the semiconductor sample dependent

on the excess charge carrier density in the semiconductor sample produced by the illumination; and a processor coupled to the reference illumination detector and the measurement device for producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of the semiconductor sample dependent upon a reference illumination measurement of the reference illumination detector, known physical properties of the semiconductor sample, and the measured physical response of the semiconductor sample.

The light source may comprises:

one or more monochromatic or substantially monochromatic light sources;
one or more lasers;
one or more lasers with filtering;
a broad spectrum light source;
a broad spectrum light source that is filtered;
a high power light emitting diode;
a high power light emitting diode with filtering;
an array of light emitting diodes; and
an array of light emitting diodes with filtering.

The system may further comprise a signal driver coupled to the light source for controlling the time-varying absolute photon flux illuminating the semiconductor sample. The signal driver is coupled to the light source and the processor, the signal driver being at least partly implemented using the processor.

Regarding the second aspect of the invention, the processor derives and analyzes a charge carrier generation rate per unit volume signal dependent upon the absolute value of the photon flux of the reference illumination measurement and the physical properties of the semiconductor sample.

The physical properties of the semiconductor sample may comprise the thickness, the wavelength-dependent optical absorption coefficient, and the wavelength-dependent reflectance of the semiconductor sample.

Regarding the second aspect of the invention, the reference illumination detector and the semiconductor sample may be alternately arrangable in the same position relative to the light source for alternately measuring the photon flux incident upon the semiconductor sample, and the physical response of the semiconductor sample, under the same nominal illumination conditions. The reference illumination detector may measure a photon flux essentially equivalent to the absolute photon flux of the illumination that would be incident upon the semiconductor sample. The system may further comprise a beam splitter disposed between the light source and the semiconductor sample to direct at least a portion of the illumination to the reference illumination detector. The reference illumination detector and the semiconductor sample may be arranged in a substantially non-parallel orientation relative to each other. The reference illumination detector measures the relative photon flux of the illumination. A separate measurement may be required to calibrate the measured relative photon flux to derive an absolute value of the photon flux incident upon the semiconductor sample. The ratio between the measured relative photon flux and the absolute photon flux incident upon the semiconductor sample may be determined based on the design of the beam splitter. The physical response of the semiconductor sample may comprise at least one of relative photoluminescence, relative photoconductance, relative free carrier absorption, and relative free carrier emission.

Regarding the second aspect of the invention, the reference illumination detector and the semiconductor sample may be arranged in a substantially parallel orientation in substantially the same plane. The reference illumination detector may measure a photon flux essentially equivalent to the absolute photon flux of the illumination incident upon the semiconductor sample. The physical response of the semiconductor sample may comprise at least one of photoluminescence, photoconductance, free carrier absorption, and free carrier emission.

The system may comprise at least two measurement devices for measuring at least two physical responses. The measurement device may comprise an optical measurement device for measuring the physical response of the semiconductor sample. The measurement device may comprise an electrical measurement device for measuring the physical response of the semiconductor sample. The electrical measurement device may comprise an inductively coupled radiofrequency (RF) bridge for measuring photoconductance. The electrical measurement device may comprise a microwave reflectance, transmission or absorption measurement device. The at least two physical responses may be photoluminescence and photoconductance. The measurements may be performed simultaneously or substantially simultaneously under the same illumination produced by the light source. Alternatively, the measurements may be performed sequentially using reproducible illumination produced by the light source, a signal driver being coupled to the light source for controlling a reproducible pulse profile of the illumination.

The system may perform calibration for quasi-steady-state, charge-carrier-lifetime measurements.

The calibration factor A_i may be determined iteratively based on the relationship between $A_i \cdot I_{PL}$, and a weighted average over the volume of the the semiconductor sample of $B \cdot n \cdot p$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, n is the electron density and p is the hole density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate and the time derivative of the weighted average.

The calibration factor A_i may be determined iteratively based on the relationship between $A_i \cdot I_{PL}$, and a weighted average over the volume of the the semiconductor sample of $B \cdot n \cdot p$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, n is the electron density and p is the hole density, and

based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate.

The calibration factor A_i may be determined iteratively based on the relationship, $A_i \cdot I_{PL}$, and $B \cdot (N_D + \langle\Delta n\rangle) \cdot \langle\Delta n\rangle$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, N_D is the doping density, and $\langle\Delta n\rangle$ is a weighted average over the volume of the the semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate and the time derivative of the weighted average.

The calibration factor A_i may be determined iteratively based on the relationship, $A_i \cdot I_{PL}$, and $B \cdot (N_D + \langle\Delta n\rangle) \cdot \langle\Delta n\rangle$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, N_D is the doping density, and $\langle\Delta n\rangle$ is a weighted average over the volume of the the semiconductor sample of the excess excess charge carrier density, and based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate.

The calibration factor A_i may be determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot \langle\Delta n\rangle$, where V_{PC} is the measured PC signal, μ_e is the electron mobility, μ_h is the hole mobility, and $\langle\Delta n\rangle$ is a weighted average over the volume of the the semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate and time derivative of the weighted average.

The calibration factor A_i may be determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot \langle\Delta n\rangle$, where V_{PC} is the measured PC signal, μ_e is the electron mobility, μ_h is the hole mobility, and $\langle\Delta n\rangle$ is a weighted average over the volume of

the the semiconductor sample of the excess charge carrier density, and based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate.

The relationship governing the effective excess charge carrier lifetime τ_{eff} is defined as follows:

$$\tau_{eff} = \frac{< \Delta n(t) >}{G(t) - \frac{d < \Delta n(t) >}{dt}},$$

where $G(t)$ is the charge carrier generation rate of carriers per unit volume, and $<\Delta n(t)>$ is a weighted average over the volume of the the semiconductor sample of the excess charge carrier density.

In accordance with a further aspect of the invention, there is provided a method for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample, the method comprising: reproducibly illuminating a semiconductor sample with a time-varying absolute photon flux; contactlessly measuring a physical response of the semiconductor sample dependent on the excess charge carrier density in the semiconductor sample produced by the illumination; and producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of the semiconductor sample dependent upon a charge carrier generation rate per unit volume as a function of time, and the measured physical response of the semiconductor sample.

The charge carrier generation rate may be known by measuring the absolute photon flux as a function of time incident upon the semiconductor sample.

In accordance with a still further aspect of the invention, there is provided a method for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample, the method comprising: illuminating a semiconductor sample with a time-varying absolute photon flux; measuring the

photon flux incident upon the semiconductor sample; contactlessly measuring a physical response of the semiconductor sample dependent on the excess charge carrier density in the semiconductor sample produced by the illumination; and producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of the semiconductor sample dependent upon a reference illumination measurement, known physical properties of the semiconductor sample, and the measured physical response of the semiconductor sample.

Further aspects of the above methods may be implemented in accordance with the foregoing aspects of the above systems. These and other details are set forth hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention are described hereinafter with reference to the drawings, in which:

FIG. 1 is a graph of apparent effective excess charge carrier lifetimein units of microseconds (μs) versus excess charge carrier density Δn in units of inverse centimeter cubed ($\Delta n/cm^{-3}$), showing numerical simulation (dotted lines) and experimental data (solid lines) in accordance with an embodiment of the invention;

FIG. 2 is a graph of experimentally measured effective excess charge carrier lifetime in units of μs versus $\Delta n/cm^{-3}$ for a 235 μm-thick textured n-type silicon wafer using various techniques, two of which Quasi-Steady-State Photoluminescence (QSS-PL) and Quasi-Steady-State Photoconductance (QSS-PC) have been carried out using an embodiment of the invention;

FIG. 3 is a graph of normalized charge carrier generation rate per unit volume and normalized excess carrier concentration versus time in seconds from an intermediate mode photoluminescence (PL) experiment carried out close to quasi-steady state conditions;

FIG. 4 is a block diagram of a system for producing self consistently a calibration constant A_i for use in excess charge carrier lifetime measurements in a semiconductor sample;

FIG. 5 is a high-level flow diagram of a method of producing self consistently a calibration constant A_i for use in excess charge carrier lifetime measurements in a semiconductor sample;

FIG. 6 is a more detailed flow diagram of the step of determining the charge carrier generation rate of Fig. 5;

FIG. 7 is a further detailed flow diagram of the step of producing self consistently the calibration constant A_i of Fig. 5;

FIG. 8 is a block diagram of another system for producing self consistently a calibration constant A_i for use in excess charge carrier lifetime measurements in a semiconductor sample in accordance with a further embodiment of the invention; and

FIG. 9 is a block diagram of still another arrangement for producing self consistently a calibration constant A_i for use in excess charge carrier lifetime measurements in a semiconductor sample;

Fig. 10 is a cross-sectional diagram of a semiconductor sample showing incident illumination, reflected illumination and generation of charge carriers;

Fig. 11 is a plot of the generation of charge carriers as a function of time in response to a pulse profile of illumination showing the rising and falling branches of the charge carrier generation rate; and

Fig. 12 is a plot of effective excess charge carrier lifetime τ_{eff} as a function of Δn, showing hysteresis from the rising and falling branches of Fig. 11.

DETAILED DESCRIPTION

Methods and systems for producing self-consistently a calibration constant A_i for use in determining excess charge carrier lifetime measurements in a semiconductor sample are described. In the following description, numerous specific details, including semiconductor materials and structures, physical response measurement devices, particular light sources, and the like are set forth. However, from this disclosure, it will be apparent to those skilled in the art that modifications and/or substitutions may be made without departing from the scope and spirit of the invention. In other circumstances, specific details may be omitted so as not to obscure the invention.

Where reference is made in any one or more of the accompanying drawings to steps and/or features, which have the same or like reference numerals, those steps and/or features have for the purposes of this description the same function(s) or operation(s), unless the contrary intention appears.

In the context of this specification, the word "comprising" has an open-ended, non-exclusive meaning: "including principally, but not necessarily solely", but neither "consisting essentially of" nor "consisting only of". Variations of the word "comprising", such as "comprise" and "comprises", have corresponding meanings.

The methods or portions of the methods may be implemented in modules. A module, and in particular its functionality, can be implemented in either hardware or software. In the software sense, a module is a process, program, or portion thereof that usually performs a particular function or related functions. Such software may be implemented in C, C++, JAVA, JAVA BEANS, Fortran, or a combination thereof, for example, but may be implemented in any of a number of other programming

languages/systems, or combinations thereof. In the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it may form at least a portion of an entire electronic circuit such as a Field Programmable Gate Arrays (FPGA), Application Specific Integrated Circuit (ASIC), and the like. A physical implementation may also comprise configuration data for a FPGA, or a layout for an ASIC, for example. Still further, the description of a physical implementation may be in EDIF netlisting language, structural VHDL, structural Verilog, or the like. Numerous other possibilities exist. Those skilled in the art will appreciate that the system may also be implemented as a combination of hardware and software modules.

Some portions of the following description are presented in terms of algorithms and representations of operations on data within a computer system or other device capable of performing computations. Such algorithmic descriptions and representations may be used by those skilled in the art to convey the substance of their work to others skilled in the art. An algorithm is a sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical, magnetic, or electromagnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. These signals may be referred to as bits, values, elements, symbols, characters, terms, numbers, or the like.

The above and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to such quantities. Unless specifically stated otherwise, and as apparent from the following, discussions utilizing terms such as "producing", "calculating", "determining", "obtaining", "analyzing", "storing", "forwarding", "using", "controlling" or the like, refer to the action and processes of a computer system, or a similar electronic computing device. Such a system or device manipulates and transforms data represented as physical quantities within the registers and memories of the computer system into other data similarly

represented as physical quantities within the computer system registers, memories, or another form of storage, transmission or display devices.

Apparatuses and systems for performing the operations of the methods are also described. Such an apparatus may be specifically constructed for the required purpose. Alternatively, the apparatus may comprise a general-purpose computer or another computing device (e.g., a PDA), which may be selectively activated or reconfigured by a computer program read by the computer. The algorithms presented herein are not inherently related to any particular computer or other apparatus; various general-purpose machines may be used with programs.

The embodiments of the invention also relate to a computer program(s) or software, in which method steps may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language, operating environment, and implementation thereof. A variety of programming languages, operating systems, and coding thereof may be used. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing the scope and spirit of the invention. Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially.

The computer program may be stored on any computer readable medium. The computer readable medium may comprise storage devices, such as magnetic media disks, CD-ROMs, DVDs, flash RAM devices, memory chips, memory cards, magnetic tape, other storage devices and media suitable for interfacing with and being read by a general-purpose computer, and combinations thereof. The computer readable medium may also include a hard-wired medium, such as a local area network or the Internet, or wireless medium, such as an IEEE 802.11 wireless network, a GSM mobile telephone system, PCS, and GPS. The computer program when loaded and

executed on such a general-purpose computer effectively results in an apparatus that implements the method steps of the embodiments.

The methods of the embodiments comprise particular control flows. However, different control flows can be practised without departing from the scope and spirit of the invention.

Overview

Photoluminescence (PL) is an experimental technique that is well suited for sample characterisation in photovoltaics and has some advantages (e.g., higher sensitivity, and robustness against various artifacts) compared to other more widely used techniques. The main obstacle to using PL measurements more routinely has been the perceived difficulty in the conversion of measured relative PL signals into absolute excess carrier concentration Δn. The methods described hereinafter provide a simple, accurate solution to that problem. The methods allows PL to be used as a standalone system for excess charge carrier lifetime and Suns-PL measurements, without the need for a separate calibration technique. Methods in accordance with embodiments of the invention enable conversion of relative PL or photoconductance (PC) signals, as well as other physical response signals, into an absolute excess carrier concentration Δn.

In the following description, the methods are demonstrated by comparison of self-consistently calibrated quasi-steady-state PL measurements with transient PL and with transient and quasi-steady-state PC measurements on silicon samples. While described with reference to silicon samples, the embodiments of the invention may be applied to other semiconductors. The method simplifies photoluminescence lifetime measurements and the recently introduced Suns-photoluminescence technique, since the method allows these techniques to be used in a self-contained way, without the previous requirement for a technique involving an additional experimental device measuring an alternative physical response signal or a technique using the same measurement device but being more difficult or less accurate or otherwise disadvantageous for calibration.

Measurement of the effective charge carrier lifetime, τ_{eff}, at variable illumination intensities is a characterisation technique widely used in photovoltaics research. In many cases (in particular, in PC and PL lifetime measurements), the measurement is carried out using a light pulse with slowly varying light intensity, such that the carrier concentration within the sample to be measured is under approximately steady-state conditions at all times. The terminology quasi-steady-state (QSS) is used to describe this situation. In QSS-PC or QSS-PL measurements, a significant step in the data analysis is the conversion of the measured PC or PL signal into an average excess carrier concentration, $<\Delta n>$, which is a weighted average over the volume of the the semiconductor sample. In many cases, this conversion involves the determination of a single calibration constant, denoted A_i, for the semiconductor sample. The embodiments of the invention provide a self-consistent method to determine the absolute value of A_i. For PL measurements, this is advantageous, because the method allows QSS-PL lifetime measurements to be performed independently from other experimental techniques requiring the use of another measurement device or using the same measurement device but being more difficult or less accurate or otherwise disadvantageous . For QSS-PC measurements, the self-consistent method yields accurate results in relation to previously used calibration methods.

The method uses a light pulse that is slightly too fast to yield quasi-steady-state conditions within the particular semiconductor sample and has rising and falling branches. The PL method can be used on bare wafers, partly processed solar cells and finished solar cells, for example, but the method is not restricted to wafers. Each light intensity and each excess charge carrier density Δn within the wafer are thus reached twice during each pulse, i.e. once during the rising branch and once during the falling branch of the light pulse. Two excess charge carrier lifetime values can thus be assigned to each value of the carrier concentration Δn. Both theoretical analysis and experimental data show that in case of an inaccurate calibration of the physical response measurement system, i.e. an inaccurate value of the calibration constant A_i,

the two nominal charge carrier lifetimes obtained for the same excess charge carrier concentration differ from each other, resulting in hysteresis loops in plots of the effective excess charge carrier lifetime $\tau_{eff}(\Delta n)$ over the excess charge carrier concentration Δn (as shown in FIG. 1 and described hereinafter). The nominal excess charge carrier lifetimes are both in error, but the error is different for the rising and falling branches. Hysteresis effects are minimized for the correct value of the calibration constant A_i. Variation of the calibration constant A_i during data analysis allows the accurate calibration of the system (for the particular semiconductor sample being investigated) by minimizing or removing hysteresis effects from the resulting effective excess charge carrier lifetime $\tau_{eff}(\Delta n)$ curves.

In accordance with the embodiments of the invention, calibration methods that are self-consistent may be applied to other excess charge carrier lifetime measurement techniques that can be performed in a QSS mode, such as for instance microwave reflectance photoconductance, free carrier absorption, and free carrier emission. In principle, QSS-PC includes microwave reflectance photoconductance. QSS-PC can be measured as follows: 1) inductively coupled Radio Frequency (RF) bridge and 2) microwave reflectance. Other methods of QSS-PC excess charge carrier lifetime measurement may also be possible utilizing microwave transmission or absorption. The embodiments of the invention are described in greater detail hereinafter.

Method and system for self-consistent calibration

Fig. 5 illustrates a method 500 of producing self-consistently a calibration constant A_i for use in determining excess charge carrier lifetime measurements in a semiconductor sample in accordance with an embodiment of the invention. The method 500 commences in step 510. In step 512, the semiconductor sample is illuminated with a time-varying absolute photon flux. This illumination may be reproducible. A reproducible light pulse is required if the charge carrier generation rate as a function of time is already known prior to the measurement in step 518. However, the light source may have a non–reproducible light pulse profile if the generation rate is determined based on the reference detector measurement. Steps 514

and 516 are depicted with dashed lines to indicate that these steps are not required in all cases (i.e., they are optional in certain circumstances), as described in greater detail hereinafter. In step 518, at least one physical response of the semiconductor sample is contactlessly measured. By contactlessly, the term is used herein to refer to electrically contactless. The physical response is dependent on the excess charge carrier density Δn in the semiconductor sample produced by the illumination. In step 520, a calibration constant A_i is produced self consistenly for use in determining the excess charge carrier lifetime of the semiconductor sample dependent upon the charge carrier generation rate per unit volume as a function of time, known physical properties of the semiconductor sample, and the measured physical response of the semiconductor sample. The details of step 520 are shown in Fig. 7, described hereinafter. In step 522, processing ends.

Regarding step 514 of Fig. 5, the photon flux emitted by the light source that is incident upon the semiconductor sample may be measured to provide a reference illumination measurement, which is used to determine the charge carrier generation rate. This step, however, is not required if the charge carrier generation rate as a function of time is already known and the light source is capable of producing reproducible light pulse profiles. Regarding step 516, the charge carrier generation rate of the semiconductor sample is determined. For a particular sample or type of sample, the charge carrier generation rate per unit volume as a function of time may already be known, so only the physical response as a function of time needs to be measured. The charge carrier generation rate is therefore not required to be determined. However, an initial determination of charge carrier generation rate may be required, for example, for batches of the same type of semiconductor sample to be processed. The details of step 516 are illustrated in Fig. 6, described hereinafter.

Fig. 4 illustrates a system 400 for producing self-consistently a calibration constant A_i for excess charge carrier lifetime measurements in a semiconductor sample. The calibration is not carried out in, but is typically close to, quasi steady state (QSS). The calibration provides a relationship between the PL or PC signal and Δn for a particular

sample. This relationship is used to measure Δn, which combined with the charge carrier generation rate of charge carriers yields the excess charge carrier lifetime. A light source 430 is provided for illuminating a semiconductor sample 440 with a time-varying absolute flux. Again, see the above comments regarding reproducible versus non-reproducible pulse profiles of the illumination. The light source may comprise one or more of at least one monochromatic or substantially monochromatic light source, at least one laser, at least one laser with filtering, a broad spectrum light source, a broad spectrum light source that is filtered, a high-power light emitting diode (LED), a high-power light emitting diode (LED) with filtering, an array of LEDs and an array of LEDs with filtering. In the embodiment of Fig. 4, the light source 430 may generate light with a central wavelength of 850 nm, for example. Further, for the purposes of illustration only, the semiconductor sample 440 may be an n-type silicon (Si) wafer that is 235 μm thick. At the given wavelength (λ), the light incident on the semiconductor sample 440 may be essentially fully absorbed.

The light source 430 may be coupled to a processor 410, which is depicted by a general-purpose computer in Fig. 4. The processor 410 can execute computer programs and software to perform a variety of functions and tasks, including analzying signals generated by the system 400, as described hereinafter. Preferably, a signal driver 420 is coupled between the processor 410 and the light source 430 to control a reproducible pulse profile of the light signal generated by the light source 430. Dependent upon the capabilities of the light source 430, the signal driver 420 may be implemented in software, hardware, or a combination of the two. If implemented in software, the signal driver 420 may be carried out using the processor 410, for example.

As noted above with regard to Fig. 5, it is not always necessary to measure the photon flux incident on the semiconductor sample and to determine the charge carrier generation rate per unit volume as a function of time, since the latter may already be known.

The system 400 comprises a measurement device 470 and further may comprise a relative reference illumination detector 460. In this embodiment, the reference illumination detector 460 measures relative photon flux incident upon the semiconductor sample 440 emitted by the light source 430. However, as described with reference to Fig. 8, the detector 460 may measure absolute photon flux, e.g., where the beamsplitter reflectance has been selected such that the absolute photon flux incident upon the detector 460 is the same as that incident on the sample . In the literature, the term "photon flux" is generally understood to mean absolute photon flux, in contrast to relative photon flux. However, as used in this description, the term "photon flux" per se covers both absolute photon flux and relative photon flux, while each of the latter terms is used to describe particular embodiments of the invention. The measurement device 470 contactlessly measures a physical response of the semiconductor sample 440 dependent on the excess charge carrier density Δn in the semiconductor sample 440 produced by the illumination. The measurement device 470 may measure relative photoluminescence (PL) or photoconductance (PC) excited in the semiconductor sample 440.

A beam splitter 450 may be used to split a portion of the illumination from the light source 430 incident on the semiconductor sample 440 to the relative reference illumination detector 460. In this embodiment, the relative reference illumination detector 460 measures the relative photon flux incident upon the detector 460 and produces a reference illumination measurement. A calibration of the ratio between relative and absolute flux has to be carried out.

Fig. 4 shows a particular arrangement of the semiconductor sample 440 and the relative reference illumination detector 460, however, their positions may be alternately changed relative to the light source 430. The relative reference illumination detector 460 and the semiconductor sample 440 are arranged in a substantially non-parallel orientation relative to each other, as shown in Fig. 4. In this arrangement, the orientations of the surfaces of the sample 440 and the detector 460 that the illumination is incident upon are substantially perpendicular to each other.

However, other orientations may be practiced without departing from the scope of the invention. In further embodiments described hereinafter, the relative reference illumination detector 460 and the semiconductor sample 440 may be substantially parallel in substantially the same plane.

The measuring device 470 may comprise an optical measurement device for measuring photoluminescence excited in the semiconductor sample 440, an electrical measurement device for measuring photoconductance excited in the semiconductor sample 440, or a combination thereof. PC and PL measurements can be made simultaneously, but are completely independent measurements. Making both measurements is useful, since doing so allows the same sample to be measured with both PL and PC at the same time. PC data is generally more reliable at "high" charge carrier densities (i.e. at high illumination levels), and PL data is more reliable at moderate and low charge carrier densities levels. Therefore, collecting both at the same time allows the excess charge carrier lifetime to be accurately measured at all desired charge carrier densities levels at the same time (i.e. in a single pulse or averaged data from a single set of pulses), with no change to the experimental setup. The self-consistent calibration required for the above PC and PL measurements is typically carried out at moderate to high illumination levels. Unlike conventional systems in which a previously calibrated PC apparatus is often used to calibrate PL measurements, the method in accordance with the embodiments of the invention permits both to be calibrated at the same time. For PC, the method in accordance with the embodiments of the invention is easier than the conventional calibration method and may be more accurate.

While not shown in Fig. 4, a filter or several filters may be used between the sample 440 and the measuring device 470 for passing PL/PC in the desired range while blocking the light generated by the light source 430, for example.

Both the relative reference illumination detector 460 and the measurement device 470 are coupled to the processor 410. The processor 410 receives a reference illumination

measurement (of the relative photon flux) from the relative reference illumination detector 460 and a physical response (e.g., photoluminescence or photoconductance) measurement from the measurement device 470. The physical response of the semiconductor sample 440 may alternatively be free carrier absorption or free carrier emission. The processor 410 produces self-consistently a calibration constant A_i for use in determining the excess charge carrier lifetime of the semiconductor sample 440 dependent upon the charge carrier generation rate per unit volume, physical properties of the semiconductor sample 440, and the measured physical response of the semiconductor sample 440. The processor 410 analyzes the reference illumination measurement and the photoluminescence or photoconductance measurement. More particularly, the processor 410 derives and analyzes a charge carrier generation rate per unit volume signal G(t) dependent upon the absolute value of photon flux (obtained separately using a calibrated illumination detector 480) and the physical properties of the semiconductor sample 440.

The physical properties of the semiconductor sample 440 comprise the thickness, the wavelength-dependent optical absorption coefficient, and the wavelength-dependent reflectance of the sample 440.

While the foregoing embodiment of the invention has been described with reference to a single physical response being measured, two or more physical responses may be measured. For example, the two physical responses may be photoluminescence and photoconductance. The two measurements obtained by two measurement devices 470 may be performed simultaneously or substantially simultaneously under the same illumination produced by the light source 430. Alternatively, the measurements may be performed sequentially using reproducible illumination produced by the light source 430, where the signal driver 420 is coupled to the light source 430 for controlling a reproducible pulse profile of the illumination. The measurement device 470 may comprise an optical measurement device for measuring photoluminescence, or an electrical measurement device for measuring the physical response of the semiconductor sample, or both. The electrical measurement device may be an

inductively coupled radiofrequency (RF) bridge for measuring photoconductance, or a microwave reflectance measurement device. The system performs calibration self-consistently for charge-carrier-lifetime measurements. This calibration may be used to enable carrying out true QSS measurements but is not limited to QSS measurements.

The conversion of a measured PL signal into a spatially-averaged, absolute excess carrier concentration Δn is an important step in PL lifetime measurements and also in the Suns-PL technique. In the embodiments of the invention, the conversion of relative PL signals into absolute excess carrier concentration Δn is significantly simplified. The quantities that must be known accurately in absolute units for methods in accordance with the embodiments of the invention to be applied are incident photon flux as well as thickness and reflectance and absorption coefficient at the wavelegth of light emitted by the light source 430 of the semiconductor sample. Such methods, which are discussed hereinafter with reference to PL, can also be applied to calibrate relative PC measurements.

Assuming homogeneous carrier concentrations within a semiconductor sample at all times, the evolution of the average excess carrier concentration $\Delta n(t)$ under illumination as a function of time is determined by the charge carrier generation rate $G(t)$ of charge carriers and by a total recombination rate, as follows:

$$\frac{d\Delta n(t)}{dt} = G(t) - \frac{\Delta n(t)}{\tau_{eff}[\Delta n(t)]}. \qquad (1)$$

In Eq. (1), the recombination rate is expressed in terms of an effective excess charge carrier lifetime $\tau_{eff}(\Delta n)$, which itself depends on the excess carrier concentration Δn. From Eq. (1), the effective excess charge carrier lifetime is given as follows:

$$\tau_{eff} = \frac{< \Delta n(t) >}{G(t) - \frac{d < \Delta n(t) >}{dt}}. \qquad (2)$$

where $G(t)$ is the charge carrier generation rate of carriers per unit volume as a function of time, and $\langle \Delta n(t) \rangle$ is a weighted average over the volume of the the semiconductor sample of the excess charge carrier density.

In the embodiment of Fig. 4, a calibrated illumination detector 480 measuring absolute photon flux may be positioned next to or in place of the semiconductor sample 440, so that a scaling factor can be determined for the relative reference illumination detector 460, allowing the absolute photon flux that would be incident on the sample 440 from the light source 430 to be determined.

Fig. 10 illustrates illumination 1020 incident on a semiconductor sample 1010 of thickness d and illustrates reflected illumination denoted with an arrow 1030, dependent upon the reflectance $R(\lambda)$, which is a function of illumination wavelength. Thus, the sample's thickness d is sufficient to absorb the entirety of accepted incident light to generate charge carriers , where $\alpha(\lambda)$ is the wavelength dependent absorption coefficent of the semiconductor sample. If $\alpha(\lambda)$ is not at least approximately known, it would be uncertain if all the photon flux entering the semiconductor sample 440 is absorbed. An alternative to knowing $\alpha(\lambda)$ is to measure the transmission through the semiconductor sample 440. Fig. 11 is a plot showing a corresponding pulse of charge carrier generation in the semiconductor sample in response to the pulse profile of the incident light. The pulse in Fig. 11 has a rising branch 1110 and a falling branch 1120.

The conversion of experimental relative PL intensities into absolute excess charge carrier concentration Δn may involve the iterative determination of a calibration factor A_i using the following relationship:

$$A_i \cdot I_{PL} = B \cdot (N_D + \langle \Delta n \rangle) \cdot \langle \Delta n \rangle, \qquad (4)$$

where B is the radiative recombination coefficient and N_D is the doping density. I_{PL} is the measured photoluminescence current in the PL detector 470 and $\langle \Delta n \rangle$ is a weighted average over the volume of the semiconductor sample of Δn. The

determination of the calibration factor A_i is also based on a relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate and time derivatives of: the weighted average, the generation rate, or both.

In the case of photoconductance, the calibration factor A_i may be determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot \langle \Delta n \rangle$, where V_{PC} is the measured PC signal (e.g., voltage), μ_e is the electron mobility, μ_h is the hole mobility, and $\langle \Delta n \rangle$ is is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and the weighted average and the charge carrier generation rate and time derivatives of: the weighted average, the generation rate, or both.

If the correct absolute charge carrier generation rate $G(t)$ but an incorrect calibration factor A_i is used for the analysis of experimental PL data, hysteresis effects are expected in the $\tau_{eff}(\Delta n)$ curves. The conversion of relative PL intensities into absolute excess carrier concentration Δn is reduced to the measurement of the absolute charge carrier generation rate $G(t)$ and subsequent variation of A_i during the analysis of experimental PL data until hysteresis effects in resulting $\tau_{eff}(\Delta n)$ curves are either eliminated or minimized. Thus, the calibation constant A_i can be iteratively determined, starting with an initial seed value for the calibration constant A_i. It may take several iterations until the hysteresis effects are minimized or eliminated. The measurement is self consistent when the disagreement between the rising branch and falling branch is minimized. A non-linear dependence of the PL intensity on the product of charge carrier concentrations is expected at high excess carrier concentrations Δn due to the reduced Coulomb attraction between electron and holes. This effect can either be explicitly taken into account in the analysis by using an analytical expression for the relative variation of B with injection level or the

calibration can be restricted to excess carrier concentrations $\Delta n < 10^{15}$ cm^{-3}, where B is essentially constant in the case of silicon samples.

Fig. 12 is a plot of τ_{eff} as a function of excess charge carrier density Δn, showing a theoretical curve and the hysteresis effects are indicated for the rising branch 1210 (long dashes) and the falling branch 1220 (short dashes). The correct calibration constant minimizes the hysteresis in the values of τ_{eff}.

Fig. 6 illustrates in further detail the step 516 of Fig. 5. The processing commences in step 610. In decision step 612, a check is made to determine what type of photon flux has been measured. If absolute photon flux has been measured, the charge carrier generation rate is calculated using the absolute photon flux and the physical properties of the sample at step 616. Otherwise (relative), processing continues at step 614. In decision step 614, a check is made to determine if the ratio of absolute photon flux to relative photon flux is known from calculation or the design of the system for measuring A_i. The geometry of the light source, the reference illumination detector and the semiconductor sample, the reflectance of the beam splitter, and characteristics of the reference illumination detector affect the ratio of absolute to relative photon flux. If step 614 returns false (No), processing continues at step 618 and the ratio of absolute photon flux to relative photon flux is measured. Processing then continues in step 619. Otherwise, if step 614 returns true (Yes), processing continues at step 619. In step 619, the relative photon flux measurements are converted into absolute photon flux using the ratio of absolute to relative photon flux. Processing continues at step 616. In step 616, the charge carrier generation rate is calculated using the absolute photon flux and the physical properties of the semiconductor sample. Processing then terminates at step 620.

Fig. 7 illustrates in greater detail step 520 of Fig. 5. Processing commences in step 710. In step 712, an array of charge carrier generation rate values is created as a function of time. While the term "array" is used to describe the collection of charge carrier generation rate values, step 712 is not limited to any particular data structure.

The main point is that a number of charge carrier generation rate values are created. The same principle applies to steps 716 and 718, described hereinafter. In step 714, a seed value is chosen for the calibration constant A_i. In step 716, an array of Δn values are determined as a function of time with the current calibration constant A_i. In step 718, an array of τ_{eff} values are determined as a function of Δn. In step 720, the degree of hysteresis in τ_{eff} values as a function of Δn is evaluated. In decision step 722, a check is made to determine if the evaluation shows that the hysteresis has minimized sufficiently. If step 722 returns true (Yes), processing terminates in step 726. Otherwise, if step 722 returns false (No), processing continues at step 724. In step 724, the calibration constant A_i is changed in an appropriate direction to minimize hysteresis. Processing then continues at step 715. Regarding step 724, an initial adjustment of the calibration constant may increase the hysteresis, and therefore it may be 2 or 3 iterations of step 716-724 before hysteresis starts to minimize.

Equation (4) is used to convert the relative PL or PC signals into $\Delta n(t)$ curves using a trial value of A_i. The two curves (similar to those shown in Fig. 3) are analyzed and interpreted in terms of excess charge carrier lifetime using Equation 2, yielding curves similar to those shown in Fig. 1. With correct calibration (correct value of A_i), the same excess charge carrier lifetimes are obtained in the rising and falling branches of the $\tau_{eff}(\Delta n)$ curves . However, incorrect calibration (incorrect value of calibration constant A_i) results in different excess charge carrier lifetimes (both in error, but each with a different error) in the rising and falling branches. Steps 716 to 724 are repeated using values of A_i until the hysteresis in the $\tau_{eff}(\Delta n)$ curves shown in Fig. 1 is eliminated or minimised – i.e. until the rising and falling braches of in the $\tau_{eff}(\Delta n)$ curves are aligned. The embodiments of the invention may make excess charge carrier lifetime measurements more accurate in the case of PC (which conventionally is calibrated using a different method). In the case of photoluminescence, the embodiments of the invention allow PL to be used as a self-contained method without requiring a separate calibration method using a different technique (PC for example). Instead, absolute excess charge carrier lifetime can be obtained without using PC or

another separate excess charge carrier lifetime measurement method . The utility of the embodiments of the invention is enhanced due to the superior sensitivity of PL over PC in many practical cases and its freedom from common artifacts such as the Depletion Region Modulation effect and trapping related artifacts found in PC and other excess charge carrier lifetime measurement methods.

Demonstration Using Numerically Simulated Data

The principle of calibration methods in accordance with embodiments of the invention can be demonstrated using numerically simulated data. The excess carrier profile $\Delta n(t)$ can be calculated using Equation (1) for a charge carrier generation profile with amplitude 4.6×10^{17} cm^{-3} s^{-1} and a frequency of 15.5 Hz. The effective excess charge carrier lifetime is assumed to decrease linearly from 314 μs at $\Delta n = O$ to 309 μs at $\Delta n = 10^{14}$ cm^{-3} similar to the experimentally observed excess charge carrier lifetime data that is discussed hereinafter. The doping density is assumed to be $N_D = 5\times10^{15}$ cm^{-3} (corresponding to 1 Ω cm n-type silicon). The absolute PL signal is calculated from Equation (4) using the numerical data for $\Delta n(t)$ and $A_i = 1$. These numerically simulated PL data are analyzed using Eqs. (2) and (3). The dotted lines in FIG. 1 show $\tau_{eff}(\Delta n)$ curves calculated from the numerically generated PL data for various trial values of A_i. Clear hysteresis effects are predicted even for deviations of A_i from unity of only a few percent for Ai=0.95. The minimization of such hysteresis effects in experimental $\tau_{eff}(\Delta n)$ data allows the correct scaling factor A_i to be determined and relative PL signals to be converted into absolute Δn as is demonstrated experimentally hereinafter.

This method relies on an absolute measurement of the average charge carrier generation rate $G(t)$ within the sample. A solid state light source such as a light emitting diode (LED) array with a narrow spectrum (30 nm full width at half maximum) centered at 870 nm can be used. The penetration depth for this wavelength is much shorter than the thickness of a typical silicon wafer and the absorptance $A(\hbar\omega)$ is therefore determined by the front surface reflectance R_f, i.e.,

$A(\hbar\omega) = 1 - R_f(\hbar\omega)$. As the reflectance normally varies only marginally over a few nanometers wavelength in typical bulk samples, the determination of G(t) reduces to the measurement of the incident absolute photon flux J_γ and of the front surface reflection, the latter measured at the peak emission wavelength:

$$G(t) = \frac{1}{d} \cdot J_\gamma \cdot (1 - R_{f,870nm}), \qquad (5)$$

where d is the thickness of the sample.

The incident absolute photon flux can be measured with a calibrated photodetector. The front surface reflectance has only a minor impact on the accuracy of the method, especially in textured samples or in planar samples with an antireflection coating for which the value of $R_{f,870\ nm}$ is typically on the order of only a few percent. Because the charge carrier generation rate is linear in $1\text{-}R_f$, an absolute error in the reflectance of a few percent only results in a corresponding relative variation of G(t), allowing the self-consistent calibration to be carried out even if the reflectance R_f can only be estimated.

PL and PC measurements have been carried out using an 870 nm LED array with 1.5 W cw optical output power for excitation. The incident light intensity was measured with a calibrated Si sensor, and the reflectance of each investigated sample was measured with a Cary 500 spectrophotometer.

Excess charge carrier lifetime measurements were carried out on a textured 1 Ω cm n-type silicon sample with a thickness of 235 μm, passivated with thermal oxides and a phosphorous diffusion on both sides. The relative PL signal from that sample was measured for a charge carrier generation profile with frequency 15.5 Hz and a peak amplitude corresponding to an absolute charge carrier generation rate of 4.6×10^{17} cm^{-3}. The excess carrier concentration was determined from the relative PL data according to Eq. (4) with various trial values for A_i. The resulting effective excess charge carrier lifetime $\tau_{eff}(\Delta n)$ curves are plotted as a function of the injection level in

FIG. 1 (solid lines). Only one value for A_i leads to consistent effective excess charge carrier lifetime $\tau_{eff}(\Delta n)$ data from the rising and the falling branches of the wave form, with significant hysteresis effects for all other scaling factors (note that the experimental trial values far A_i were normalized in Fig. 1 to the value of A_i that minimizes the hysteresis effects). The close agreement between the experimental and the theoretical data shown in FIG. 1 is a strong indication of the viability and accuracy of the method.

An experimental check of the accuracy of the self-consistently calibrated PL lifetime measurement was carried out by comparison with transient PL experiments, which have the advantage that transient PL experiments give the effective excess charge carrier lifetime τ_{eff} in absolute units independent of the calibration of the system, provided the latter is linear. The transient PL lifetime data (indicated black, dotted line) are shown in Fig. 2 together with results from a self consistently calibrated quasi-steady-state PL measurement, in which the scaling factor A_i that was determined from the measurements (black, solid line) shown in Fig. 1 was used. The transient and the self -consistently determined values for the effective excess charge carrier lifetime $\tau_{eff}(\Delta n)$ agree to within 6% over the whole injection level range studied.

To confirm these results with an independent experimental method, photoconductance decay and QSS-PC were measured on the same sample using a calibrated PC setup (Sinton Consulting WCT 100). In PC measurements, the measured relative signal is converted into absolute excess conductivity $\Delta\sigma$ using linear (C_{lin}) and quadratic calibration factors. However, in typical PC setups this relation is a good approximation linear at low injection levels, and the quadratic calibration factor can be neglected. The commercial PC setup used here was factory calibrated using a set of silicon wafers with variable resistivity.

Fig. 2 shows the excess charge carrier lifetime from a transient pbotoconductance measurement (dashed line), which agrees well with the transient PL results with deviations <2%. The QSS-PC lifetime was measured using the same waveform as for the self consistent PL measurements from Fig. 1. Analyzing the data using the factory settings for C_{lin} yielded a excess charge carrier lifetime of only 180 µs and also produced pronounced hysteresis effects. Thus, the linear PC calibration factor C_{lin} has changed due to modifications of the setup. The calibration is particularly sensitive to the distance between the wafer and the PC coil. Variation of C_{lin} in the analysis allowed these hysteresis effects to be eliminated in the same way as shown in Fig. 1 for PL. The excess charge carrier lifetime curve for the value of C_{lin} that minimizes hysteresis in the PC (solid line in Fig. 2) was found to be the one that also matches the transient PC and the PL data best, which gives another strong indication of the accuracy of the method.

Other silicon wafers with variable doping density, doping type, thickness, surface texture, and material quality were investigated and found to have similarly good agreement between self-consistently calibrated QSS-PL data on the one hand and the transient PL, transient PC and self-consistently calibrated QSS-PC on the other hand. The experiments showed that the calibration factor C_{lin} determined self-consistently for the PC setup varies by up to 30% from one wafer to the other. For PC users, the measurements obtained clearly demonstrate that a self-consistent calibration of the linear calibration factor C_{lin} is necessary for each type of sample to achieve more accurate QSS-PC lifetime measurements.

In principle, comparison of a transient measurement with a quasi steady state measurement is sufficient to calibrate PL (or PC) measurements. However, on low excess charge carrier lifetime samples, transient PL measurements can be difficult due to experimental limitations of the data acquisition rate or die bandwidth of the PL detection system, which typically comprises a photodetector and a low noise preamplifier. The self-consistent method is carried out in an intermediate regime between transient and QSS and can be carried out close to quasi-steady-state

conditions, i.e., with comparatively slow wave forms, thereby extending the range of excess charge carrier lifetimes to which the method can be applied. This point is elucidated by the experimental data of the normalized $\Delta n(t)$ and the normalized $G(t)$ shown in Fig. 3. The small shift between $G(t)$ and Δn (t) is sufficient to produce the pronounced hysteresis effects shown in Fig. 1, which in turn allowed A_i to be determined accurately as shown in Fig. 2.

Other Configurations

Fig. 8 illustrates a system 800 for producing self-consistently a calibration factor for excess charge carrier lifetime measurements. The system 800 comprises a computer 810, a signal driver 820, a light source 830, a beam splitter 850, and a measurement device 870 that contactlessly measures a physical response of the semiconductor sample 840. These features are configured in the manner depicted in Fig. 4 and have like numbers (e.g. the light source 430 of Fig. 4 is numbered 830 in Fig. 8). For the sake of brevity, description of these features and their functions are not repeated here. In this embodiment, the reference illumination detector 860 measures the absolute value of photon flux, rather the relative photon flux measured by detector 460. This may be achieved for example by choosing a suitable ratio of transmission to reflection for the beamsplitter

Fig. 9 illustrates yet another system 900 for producing self-consistently a calibration factor for excess charge carrier lifetime measurements. The system 900 comprises a computer 910, a signal driver 920, a light source 930, and a measurement device 970 that contactlessly measures a physical response of the semiconductor sample 940. These features are configured in the manner depicted in Fig. 4 and have like numbers (e.g. the light source 430 of Fig. 4 is numbered 930 in Fig. 9). For the sake of brevity, description of these features and their functions are not repeated here. In this embodiment, the reference illumination detector 860 also measures the absolute value of photon flux. However, in this embodiment, a beam splitter is not used, and instead the reference illumination detector is position adjacent to the sample 940. Thus, for

substantially uniform illumination, the detector 960 and the sample 940 are similarly illuminated.

Computer Implementation

The methods according to the embodiments of the invention may be practiced using one or more general-purpose computer systems, handheld computing devices, and other suitable computing devices, in which the processes described with reference to Figs. 1-13 may be implemented at least in part as software, such as an application program executing within the computer system 410 of Fig. 4 or a handheld computing device. In particular, instructions in the software that are carried out by the computer effect the steps in the method, at least in part. Software may include one or more computer programs, including application programs, an operating system, procedures, rules, data structures, and data. The instructions may be formed as one or more code modules, each for performing one or more particular tasks. The software may be stored in a computer readable medium, comprising one or more of the storage devices described below, for example. The computer system loads the software from the computer readable medium and then executes the software. Fig. 13 depicts an example of a computer system 1300 with which the embodiments of the invention may be practiced. A computer readable medium having such software recorded on the medium is a computer program product. The use of the computer program product in the computer system may effect an advantageous apparatus in accordance with the embodiments of the invention.

Fig. 13 illustrates the computer system 13 in block diagram form, coupled to a wireless network 1320. An operator may use the keyboard 1330 and/or a pointing device such as the mouse 1332 (or touchpad, for example) to provide input to the computer 1350. The computer system 1300 may have any of a number of output devices, including line printers, laser printers, plotters, and other reproduction devices connected to the computer. The computer system 1300 can be connected to one or more other computers via a communication interface 1364 using an appropriate

communication channel 1340. The computer network 1320 may comprise a wireless local area network (WLAN), for example.

The computer 1350 may comprise a processing unit 1366 (e.g., one or more central processing units), memory 1370 which may comprise random access memory (RAM), read-only memory (ROM), or a combination of the two, input/output (IO) interfaces 1372, a graphics interface 1360, and one or more storage devices 1362. The storage device(s) 1362 may comprise one or more of the following: a floppy disc, a hard disc drive, a magneto-optical disc drive, CD-ROM, DVD, a data card or memory stick, flash RAM device, magnetic tape or any other of a number of non-volatile storage devices well known to those skilled in the art. While the storage device is shown directly connected to the bus in Fig. 13, such a storage device may be connected through any suitable interface, such as a parallel port, serial port, USB interface, a Firewire interface, a wireless interface, a PCMCIA slot, or the like. For the purposes of this description, a storage unit may comprise one or more of the memory 1370 and the storage devices 1362 (as indicated by a dashed box surrounding these elements in Fig. 13).

Each of the components of the computer 1350 is typically connected to one or more of the other devices via one or more buses 1380, depicted generally in Fig. 13, that in turn comprise data, address, and control buses. While a single bus 1380 is depicted in Fig. 13, it will be well understood by those skilled in the art that a computer or other electronic computing device, such as a PDA, may have several buses including one or more of a processor bus, a memory bus, a graphics card bus, and a peripheral bus. Suitable bridges may be utilized to interface communications between such buses. While a system using a CPU has been described, it will be appreciated by those skilled in the art that other processing units capable of processing data and carrying out operations may be used instead without departing from the scope and spirit of the invention.

The computer system 1300 is simply provided for illustrative purposes, and other configurations can be employed without departing from the scope and spirit of the invention. Computers with which the embodiment can be practiced comprise IBM-PC/ATs or compatibles, laptop/notebook computers, one of the Macintosh (TM) family of PCs, Sun Sparcstation (TM), a PDA, a workstation or the like. The foregoing are merely examples of the types of devices with which the embodiments of the invention may be practiced. Typically, the processes of the embodiments, described hereinafter, are resident as software or a program recorded on a hard disk drive as the computer readable medium, and read and controlled using the processor. Intermediate storage of the program and intermediate data and any data fetched from the network may be accomplished using the semiconductor memory.

In some instances, the program may be supplied encoded on a CD ROM or a floppy disk, or alternatively could be read from a network via a modem device connected to the computer, for example. Still further, the software can also be loaded into the computer system from other computer readable medium comprising magnetic tape, a ROM or integrated circuit, a magneto-optical disk, a radio or infra-red transmission channel between the computer and another device, a computer readable card such as a PCMCIA card, and the Internet and Intranets comprising email transmissions and information recorded on websites and the like. The foregoing is merely an example of relevant computer readable mediums. Other computer readable mediums may be practiced without departing from the scope and spirit of the invention.

A small number of embodiments of the invention regarding methods, apparatuses and systems for producing self consistently a calibration factor A_i for use in determining a excess charge carrier lifetime in a semiconductor sample have been described. In the light of the foregoing, it will be apparent to those skilled in the art in the light of this disclosure that various modifications and/or substitutions may be made without departing from the scope and spirit of the invention.

CLAIMS

We claim:

1. A system for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample, said system comprising:

a light source for reproducibly illuminating a semiconductor sample with a time-varying absolute photon flux;

a measurement device for contactlessly measuring a physical response of said semiconductor sample dependent on the excess charge carrier density in said semiconductor sample produced by said illumination; and

a processor coupled to said measurement device for producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of said semiconductor sample dependent upon a charge carrier generation rate per unit volume as a function of time, and said measured physical response of said semiconductor sample.

2. The system according to claim 1, wherein said charge carrier generation rate is known by measuring the absolute photon flux as a function of time incident upon said semiconductor sample and is dependent upon known physical properties of said semiconductor sample.

3. A system for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample, said system comprising:

a light source for illuminating a semiconductor sample with a time-varying absolute photon flux;

a reference illumination detector to measure the photon flux incident upon said semiconductor sample emitted by said light source;

a measurement device for contactlessly measuring a physical response of said semiconductor sample dependent on the excess charge carrier density in said semiconductor sample produced by said illumination; and

a processor coupled to said reference illumination detector and said measurement device for producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of said semiconductor sample dependent upon a reference illumination measurement of said reference illumination detector, known physical properties of said semiconductor sample, and said measured physical response of said semiconductor sample.

4. The system according to any one of claims 1 to 3, wherein said light source comprises at least one of:

one or more monochromatic or substantially monochromatic light sources;

one or more lasers;

one or more lasers with filtering;

a broad spectrum light source;

a broad spectrum light source that is filtered;

a high power light emitting diode;

a high power light emitting diode with filtering;

an array of light emitting diodes; and

an array of light emitting diodes with filtering.

5. The system according to any one of claims 1 to 4, further comprising a signal driver coupled to said light source for controlling said time-varying absolute photon flux illuminating said semiconductor sample.

6. The system according to claim 5, wherein said signal driver is coupled to said light source and said processor, said signal driver being at least partly implemented using said processor.

7. The system according to claim 3, wherein said processor derives and analyzes a charge carrier generation rate per unit volume signal dependent upon the absolute value of the photon flux of said reference illumination measurement and said physical properties of said semiconductor sample.

8. The system according to any one of claims 1 to 7, wherein said physical properties of said semiconductor sample comprise the thickness, the wavelength-dependent optical absorption coefficient, and the wavelength-dependent reflectance of said semiconductor sample.

9. The system according to any one of claims 3 to 8, wherein said reference illumination detector and said semiconductor sample are alternately arrangable in the same position relative to said light source for alternately measuring said photon flux incident upon said semiconductor sample, and said physical response of said semiconductor sample, under the same nominal illumination conditions.

10. The system according to claim 9, wherein said reference illumination detector measures a photon flux essentially equivalent to the absolute photon flux of said illumination that would be incident upon said semiconductor sample.

11. The system according to any one of claims 3 to 9, further comprising a beam splitter disposed between said light source and said semiconductor sample to direct at least a portion of said illumination to said reference illumination detector.

12. The system according to claim 11, wherein said reference illumination detector and said semiconductor sample are arranged in a substantially non-parallel orientation relative to each other.

13. The system according to claim 11 or 12, wherein said reference illumination detector measures the relative photon flux of said illumination.

14. The system according to claim 13, wherein a separate measurement is required to calibrate the measured relative photon flux to derive an absolute value of said photon flux incident upon said semiconductor sample.

15. The system according to claim 13, wherein the ratio between the measured relative photon flux and the absolute photon flux incident upon said semiconductor sample is determined based on the design of said beam splitter.

16. The system according to claim 12, wherein said physical response of said semiconductor sample comprises at least one of relative photoluminescence, relative photoconductance, relative free carrier absorption, and relative free carrier emission.

17. The system according to any one of claims 3 to 8, wherein said reference illumination detector and said semiconductor sample are arranged in a substantially parallel orientation in substantially the same plane.

18. The system according to claim 17, wherein said reference illumination detector measures a photon flux essentially equivalent to the absolute photon flux of said illumination incident upon said semiconductor sample.

19. The system according to 16 or 17, wherein said physical response of said semiconductor sample comprises at least one of photoluminescence, photoconductance, free carrier absorption, and free carrier emission.

20. The system according to claim 16 or 18, comprising at least two measurement devices for measuring at least two physical responses.

21. The system according to any one of claims 1 to 20, wherein said measurement device comprises an optical measurement device for measuring said physical response of said semiconductor sample.

22. The system according to any one of claims 1 to 21, wherein said measurement device comprises an electrical measurement device for measuring said physical response of said semiconductor sample.

23. The system according to claim 22, wherein said electrical measurement device comprises an inductively coupled radiofrequency (RF) bridge for measuring photoconductance.

24. The system according to claim 22, wherein said electrical measurement device comprises a microwave reflectance, transmission or absorption measurement device.

25. The system according to any one of claims 20 to 24, said at least two physical responses are photoluminescence and photoconductance.

26. The system according to claim 20 or 25, wherein said measurements are performed simultaneously or substantially simultaneously under the same illumination produced by said light source.

27. The system according to claim 20 or 25, wherein said measurements are performed sequentially using reproducible illumination produced by said light source, a signal driver being coupled to said light source for controlling a reproducible pulse profile of said illumination.

28. The system according to any one of claims 1 to 27, wherein said system performs calibration for quasi-steady-state, charge-carrier-lifetime measurements.

29. The system according to any one of claims 1 to 28, wherein said calibration factor A_i is determined iteratively based on the relationship between

$A_i \cdot I_{PL}$, and a weighted average over the volume of the said semiconductor sample of $B \cdot n \cdot p$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, n is the electron density and p is the hole density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and the charge carrier generation rate and the time derivative of said weighted average.

30. The system according to any one of claims 1 to 28, wherein said calibration factor A_i is determined iteratively based on the relationship between $A_i \cdot I_{PL}$, and a weighted average over the volume of the said semiconductor sample of $B \cdot n \cdot p$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, n is the electron density and p is the hole density, and based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and the charge carrier generation rate.

31. The system according to any one of claims 1 to 28, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot I_{PL}$, and $B \cdot (N_D + <\Delta n>) \cdot <\Delta n>$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, N_D is the doping density, and $<\Delta n>$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate and the time derivative of said weighted average.

32. The system according to any one of claims 1 to 28, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot I_{PL}$, and $B \cdot (N_D + <\Delta n>) \cdot <\Delta n>$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, N_D is the doping density, and $<\Delta n>$ is a weighted average over the volume of the said semiconductor sample of the excess excess charge carrier density, and based on a time dependent relationship between the

effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate.

33. The system according to any one of claims 1 to 28, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot \langle \Delta n \rangle$, where V_{PC} is the measured PC signal, μ_e is the electron mobility, μ_h is the hole mobility, and $\langle \Delta n \rangle$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate and time derivative of said weighted average.

34. The system according to any one of claims 1 to 28, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot \langle \Delta n \rangle$, where V_{PC} is the measured PC signal, μ_e is the electron mobility, μ_h is the hole mobility, and $\langle \Delta n \rangle$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate.

35. The system according to claim 29, 31 or 33, wherein said relationship governing the effective excess charge carrier lifetime τ_{eff} is defined as follows:

$$\tau_{eff} = \frac{< \Delta n(t) >}{G(t) - \frac{d < \Delta n(t) >}{dt}},$$

where $G(t)$ is said charge carrier generation rate of carriers per unit volume, and $\langle \Delta n(t) \rangle$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density.

36. A method for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample, said method

comprising:

reproducibly illuminating a semiconductor sample with a time-varying absolute photon flux;

contactlessly measuring a physical response of said semiconductor sample dependent on the excess charge carrier density in said semiconductor sample produced by said illumination; and

producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of said semiconductor sample dependent upon a charge carrier generation rate per unit volume as a function of time, and said measured physical response of said semiconductor sample.

37. The method according to claim 36, wherein said charge carrier generation rate is known by measuring the absolute photon flux as a function of time incident upon said semiconductor sample and is dependent upon known physical properties of said semiconductor sample.

.

38. A method for producing self consistently a calibration factor A_i for use in determining a charge carrier lifetime in a semiconductor sample, said method comprising:

illuminating a semiconductor sample with a time-varying absolute photon flux;

measuring the photon flux incident upon said semiconductor sample;

contactlessly measuring a physical response of said semiconductor sample dependent on the excess charge carrier density in said semiconductor sample produced by said illumination; and

producing self consistently a calibration factor A_i for use in determining the excess charge carrier lifetime of said semiconductor sample dependent upon a reference illumination measurement, known physical properties of said semiconductor sample, and said measured physical response of said semiconductor sample.

39. The method according to any one of claims 36 to 38, wherein said illumination is generated by a light source comprising at least one of:

one or more monochromatic or substantially monochromatic light sources;

one or more lasers;

one or more lasers with filtering;

a broad spectrum light source;

a broad spectrum light source that is filtered;

a high power light emitting diode;

a high power light emitting diode with filtering;

an array of light emitting diodes; and

an array of light emitting diodes with filtering.

40. The method according to claim 36 to 39, wherein a signal driver coupled to said light source controls said time-varying absolute photon flux illuminating said semiconductor sample.

41. The method according to claim 40, wherein said signal driver is at least partly implemented in software using a processor.

42. The method according to claim 38, further comprising the steps of deriving and analyzing a charge carrier generation rate per unit volume signal dependent upon the absolute value of the photon flux of said reference illumination measurement and said physical properties of said semiconductor sample.

43. The method according to any one of claims 36 to 42, wherein said physical properties of said semiconductor sample comprise the thickness, the wavelength-dependent optical absorption coefficient, and the wavelength-dependent reflectance of said semiconductor sample.

44. The method according to any one of claims 38 to 43, wherein a reference illumination detector and said semiconductor sample are alternately

arrangable in the same position relative to a light source for alternately measuring said photon flux incident upon said semiconductor sample, and said physical response of said semiconductor sample, under the same nominal illumination conditions.

45. The method according to claim 44, wherein said reference illumination detector measures a photon flux essentially equivalent to the absolute photon flux of said illumination that would be incident upon said semiconductor sample.

46. The method according to any one of claims 38 to 44, wherein a beam splitter is disposed between a light source and said semiconductor sample to direct at least a portion of said illumination to a reference illumination detector.

47. The method according to claim 46, wherein said reference illumination detector and said semiconductor sample are arranged in a substantially non-parallel orientation relative to each other.

48. The method according to claim 46 or 47, wherein said reference illumination detector measures the relative photon flux of said illumination.

49. The method according to claim 48, wherein a separate measurement is required to calibrate the measured relative photon flux to derive an absolute value of said photon flux incident upon said semiconductor sample.

50. The method according to claim 48, wherein the ratio between the measured relative photon flux and the absolute photon flux incident upon said semiconductor sample is determined based on the design of said beam splitter.

51. The method according to claim 47, wherein said physical response of said semiconductor sample comprises at least one of relative photoluminescence, relative photoconductance, relative free carrier absorption, and relative free carrier emission.

52. The method according to any one of claims 38 to 43, wherein a reference illumination detector and said semiconductor sample are arranged in a substantially parallel orientation in substantially the same plane.

53. The method according to claim 52, wherein said reference illumination detector measures a photon flux essentially equivalent to the absolute photon flux of said illumination incident upon said semiconductor sample.

54. The method according to 51 or 52, wherein said physical response of said semiconductor sample comprises at least one of photoluminescence, photoconductance, free carrier absorption, and free carrier emission.

55. The method according to claim 51 or 53, wherein at least two measurement devices measure at least two physical responses.

56. The method according to any one of claims 36 to 55, wherein a measurement device comprises an optical measurement device for measuring said physical response of said semiconductor sample.

57. The method according to any one of claims 36 to 56, wherein a measurement device comprises an electrical measurement device for measuring said physical response of said semiconductor sample.

58. The method according to claim 57, wherein said electrical measurement device comprises an inductively coupled radiofrequency (RF) bridge for measuring photoconductance.

59. The method according to claim 57, wherein said electrical measurement device comprises a microwave reflectance, transmission or absorption measurement device.

60. The method according to any one of claims 55 to 59, said at least two physical responses are photoluminescence and photoconductance.

61. The method according to claim 55 or 60, wherein said measurements are performed simultaneously or substantially simultaneously under the same illumination produced by said light source.

62. The method according to claim 55 or 60, wherein said measurements are performed sequentially using said reproducible illumination produced by a light source, a signal driver being coupled to said light source for controlling the reproducible pulse profile of said illumination.

63. The method according to any one of claims 36 to 62, wherein said method performs calibration for quasi-steady-state, charge-carrier-lifetime measurements.

64. The method according to any one of claims 36 to 63, wherein said calibration factor A_i is determined iteratively based on the relationship between $A_i \cdot I_{PL}$, and a weighted average over the volume of the said semiconductor sample of $B \cdot n \cdot p$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, n is the electron density and p is the hole density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and the charge carrier generation rate and the time derivative of said weighted average.

65. The method according to any one of claims 36 to 63, wherein said calibration factor A_i is determined iteratively based on the relationship between $A_i \cdot I_{PL}$, and a weighted average over the volume of the said semiconductor sample of $B \cdot n \cdot p$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, n is the electron density and p is the hole density, and based on a time

dependent relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and the charge carrier generation rate and the charge carrier generation rate.

66. The method according to any one of claims 36 to 63, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot I_{PL}$, and $B \cdot (N_D + <\Delta n>) \cdot <\Delta n>$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, N_D is the doping density, and $<\Delta n>$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate and the time derivative of said weighted average.

67. The method according to any one of claims 36 to 63, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot I_{PL}$, and $B \cdot (N_D + <\Delta n>) \cdot <\Delta n>$, where I_{PL} is the measured PL current, B is the radiative recombination coefficient, N_D is the doping density, and $<\Delta n>$ is a weighted average over the volume of the said semiconductor sample of the excess excess charge carrier density, and based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate.

68. The method according to any one of claims 36 to 63, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot <\Delta n>$, where V_{PC} is the measured PC signal, μ_e is the electron mobility, μ_h is the hole mobility, and $<\Delta n>$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate and time derivative of said weighted average.

69. The method according to any one of claims 36 to 63, wherein said calibration factor A_i is determined iteratively based on the relationship, $A_i \cdot V_{PC} = (\mu_e + \mu_h) \cdot \langle \Delta n \rangle$, where V_{PC} is the measured PC signal, μ_e is the electron mobility, μ_h is the hole mobility, and $\langle \Delta n \rangle$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density, and based on a time dependent relationship between the effective excess charge carrier lifetime τ_{eff} and said weighted average and said charge carrier generation rate.

70. The method according to claim 64, 66 or 68, wherein said relationship governing the effective excess charge carrier lifetime τ_{eff} is defined as follows:

$$\tau_{eff} = \frac{< \Delta n(t) >}{G(t) - \frac{d < \Delta n(t) >}{dt}},$$

where $G(t)$ is said charge carrier generation rate of carriers per unit volume, and $\langle \Delta n(t) \rangle$ is a weighted average over the volume of the said semiconductor sample of the excess charge carrier density.

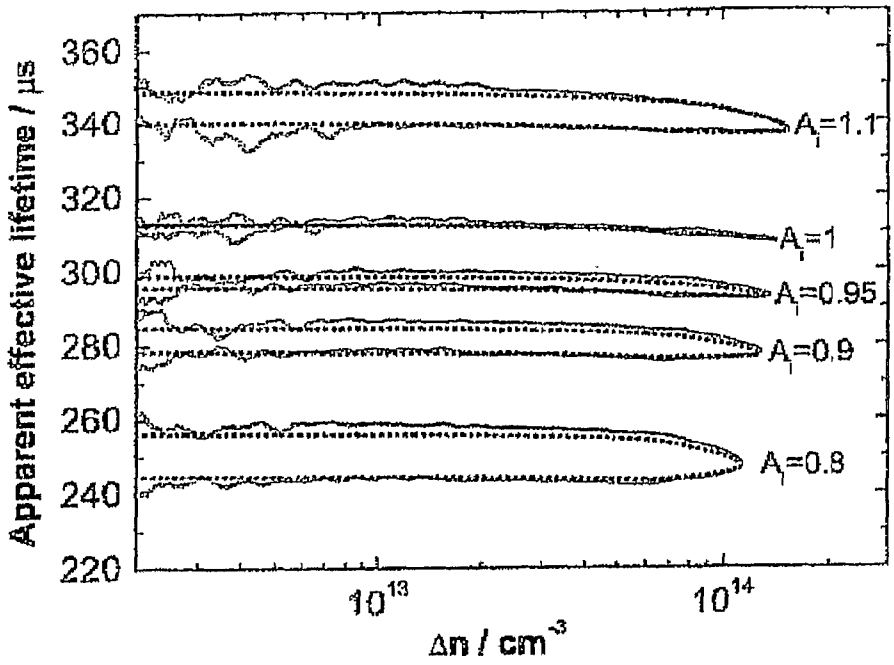

Apparent effective lifetime / µs
360
340
320
300
280
260
240
220
10^{13}
10^{14}
Δn / cm^{-3}
A_1=1.1
A_1=1
A_1=0.95
A_1=0.9
A_1=0.8

FIG. 1

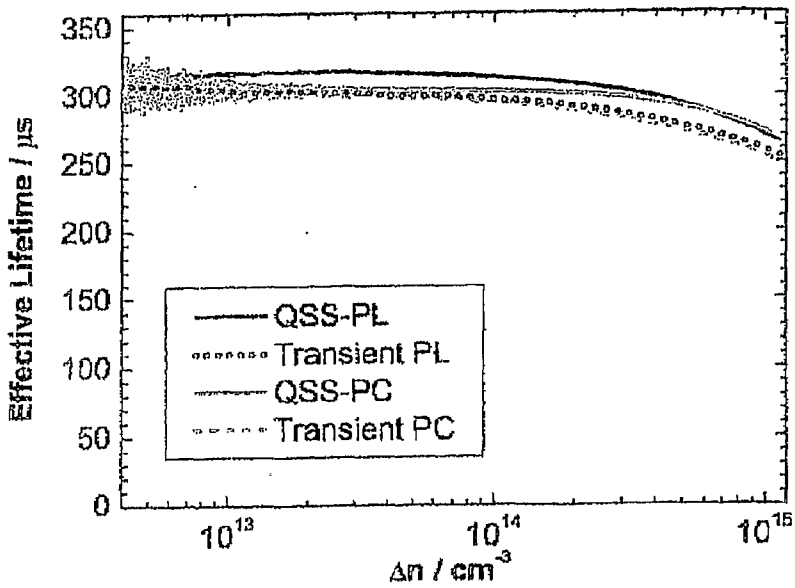

Effective Lifetime / µs
350
300
250
200
150
100
50
0
10^{13}
10^{14}
10^{15}
Δn / cm^{-3}
QSS-PL
Transient PL
QSS-PC
Transient PC

FIG. 2

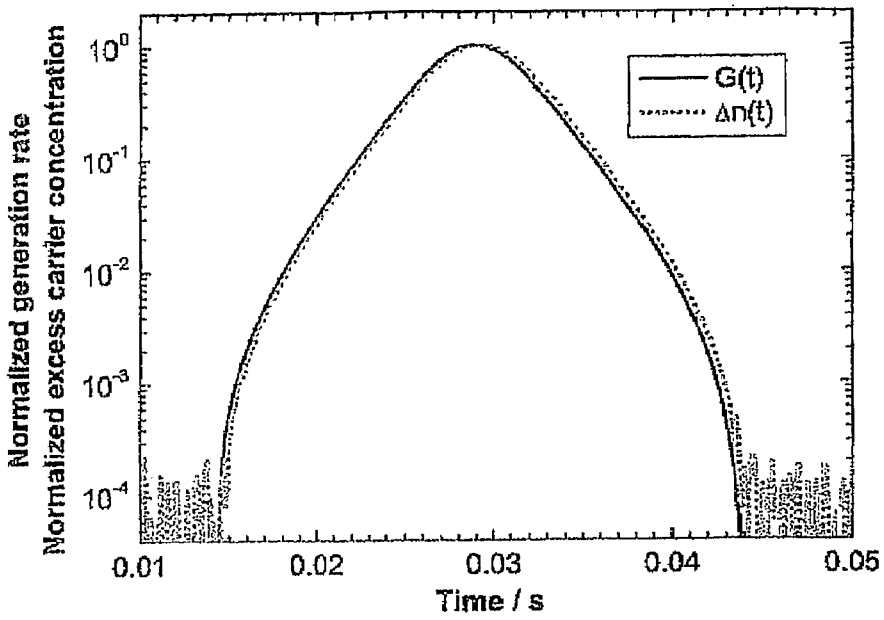

Normalized generation rate
Normalized excess carrier concentration
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
G(t)
Δn(t)
0.01
0.02
0.03
0.04
0.05
Time / s

FIG. 3

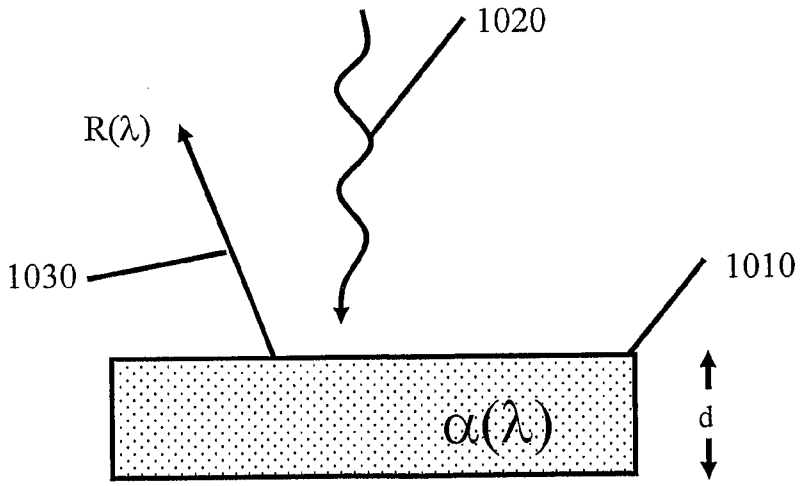

1020
R(λ)
1030
1010
α(λ)
d

FIG. 10

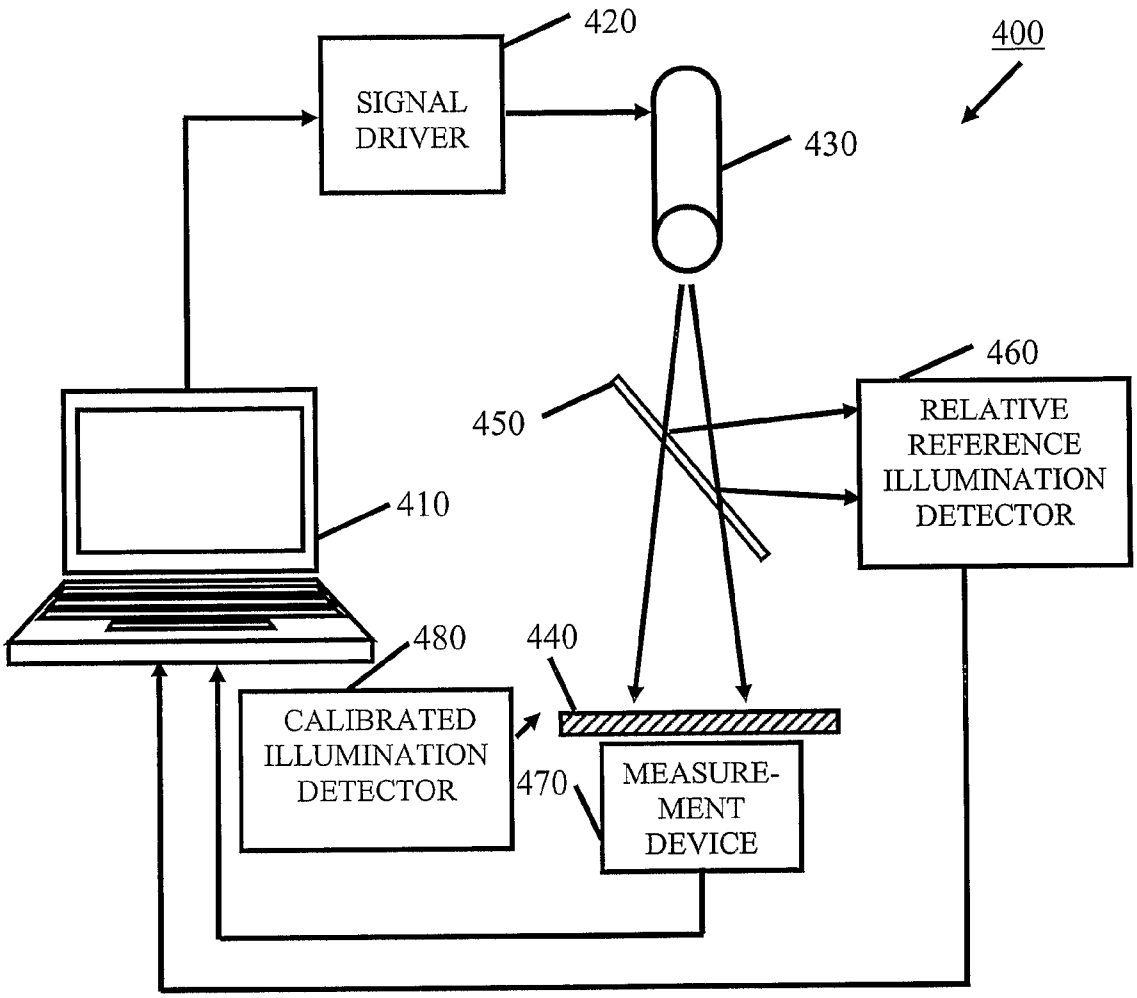

420
400
SIGNAL DRIVER
430
460
450
RELATIVE REFERENCE ILLUMINATION DETECTOR
410
480
440
CALIBRATED ILLUMINATION DETECTOR
470
MEASURE-MENT DEVICE

FIG. 4

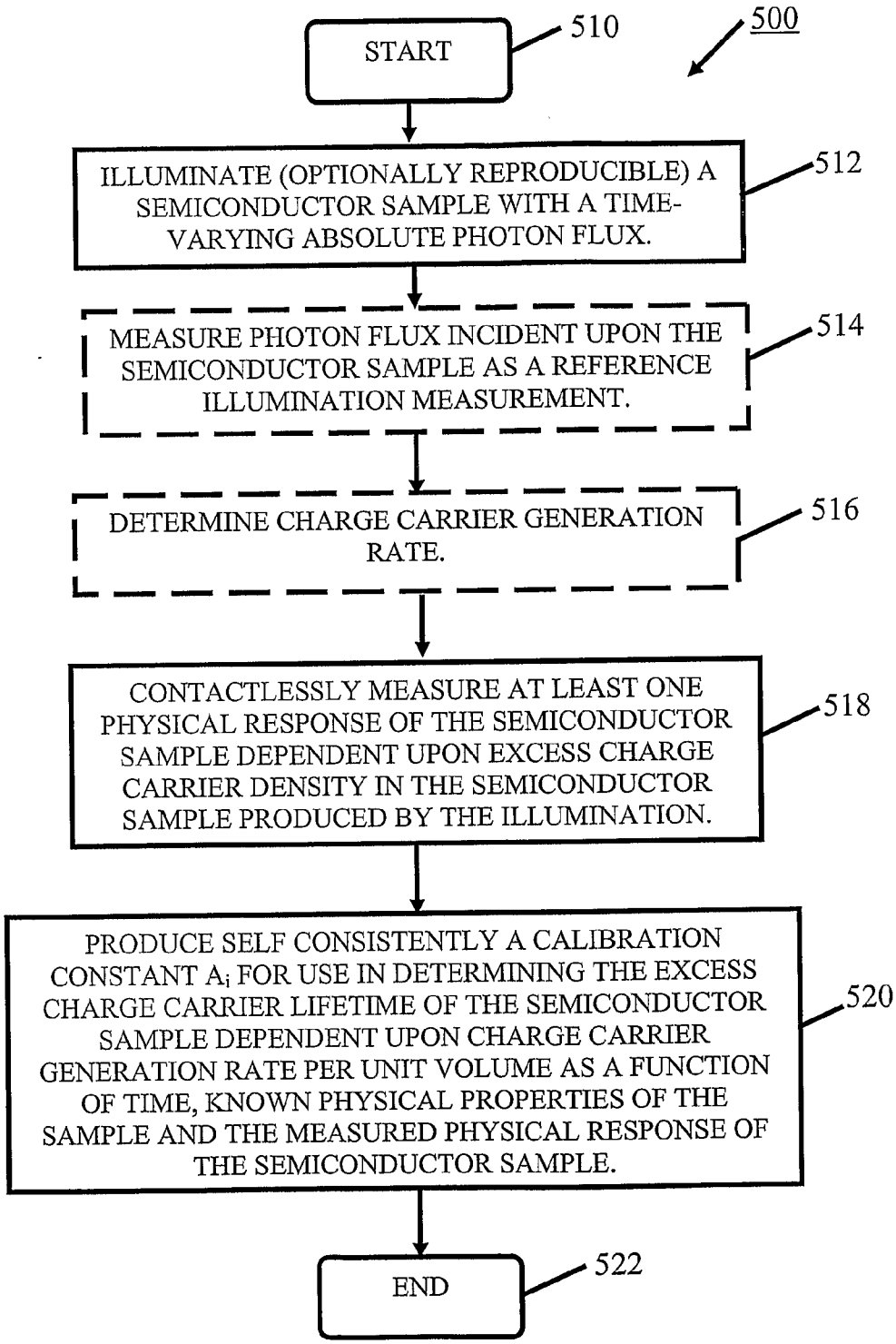

500
START
510
ILLUMINATE (OPTIONALLY REPRODUCIBLE) A SEMICONDUCTOR SAMPLE WITH A TIME-VARYING ABSOLUTE PHOTON FLUX.
512
MEASURE PHOTON FLUX INCIDENT UPON THE SEMICONDUCTOR SAMPLE AS A REFERENCE ILLUMINATION MEASUREMENT.
514
DETERMINE CHARGE CARRIER GENERATION RATE.
516
CONTACTLESSLY MEASURE AT LEAST ONE PHYSICAL RESPONSE OF THE SEMICONDUCTOR SAMPLE DEPENDENT UPON EXCESS CHARGE CARRIER DENSITY IN THE SEMICONDUCTOR SAMPLE PRODUCED BY THE ILLUMINATION.
518
PRODUCE SELF CONSISTENTLY A CALIBRATION CONSTANT A_i FOR USE IN DETERMINING THE EXCESS CHARGE CARRIER LIFETIME OF THE SEMICONDUCTOR SAMPLE DEPENDENT UPON CHARGE CARRIER GENERATION RATE PER UNIT VOLUME AS A FUNCTION OF TIME, KNOWN PHYSICAL PROPERTIES OF THE SAMPLE AND THE MEASURED PHYSICAL RESPONSE OF THE SEMICONDUCTOR SAMPLE.
520
END
522

FIG. 5

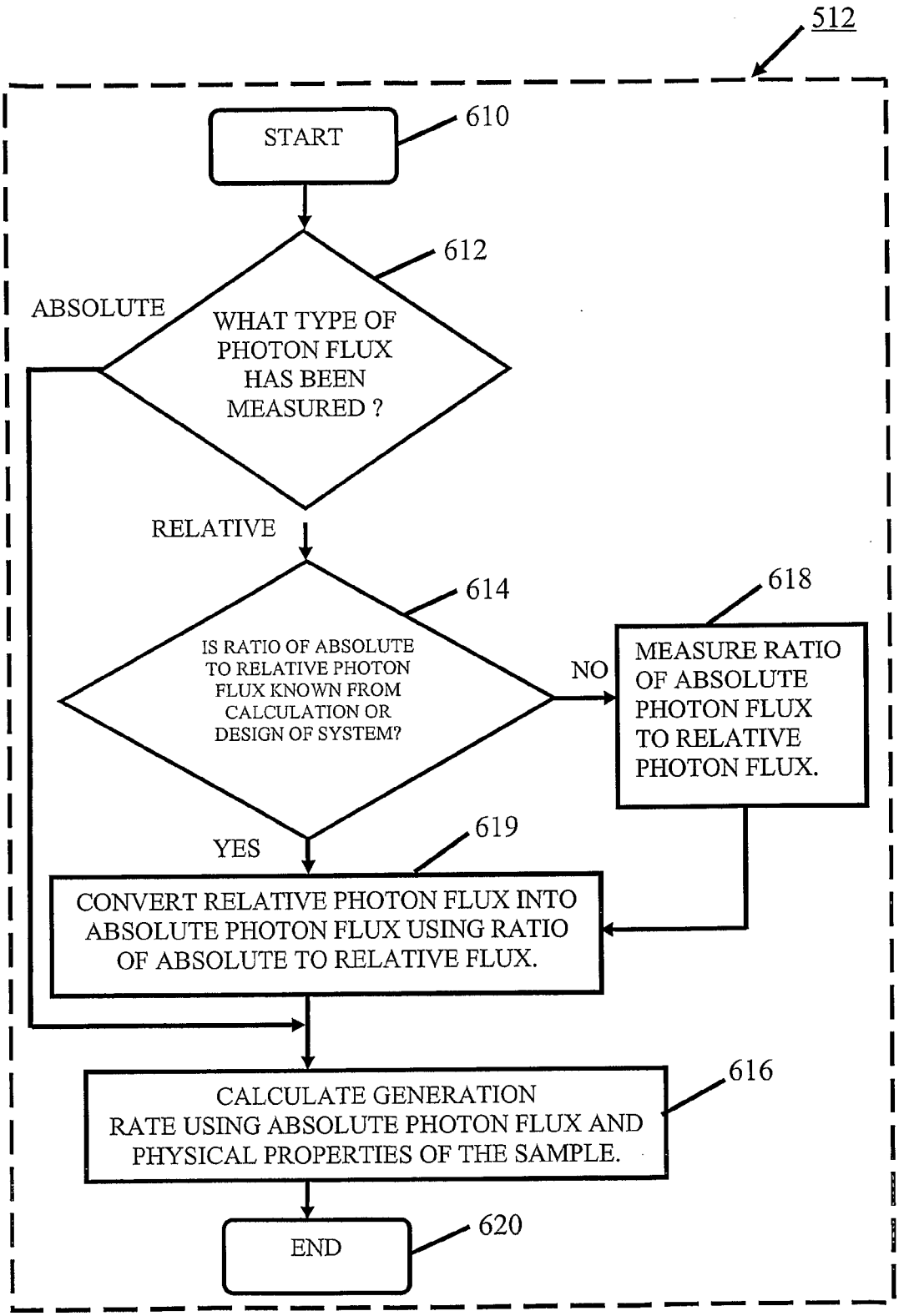

512
START
610
612
ABSOLUTE
WHAT TYPE OF PHOTON FLUX HAS BEEN MEASURED ?
RELATIVE
614
IS RATIO OF ABSOLUTE TO RELATIVE PHOTON FLUX KNOWN FROM CALCULATION OR DESIGN OF SYSTEM?
NO
618
MEASURE RATIO OF ABSOLUTE PHOTON FLUX TO RELATIVE PHOTON FLUX.
YES
619
CONVERT RELATIVE PHOTON FLUX INTO ABSOLUTE PHOTON FLUX USING RATIO OF ABSOLUTE TO RELATIVE FLUX.
CALCULATE GENERATION RATE USING ABSOLUTE PHOTON FLUX AND PHYSICAL PROPERTIES OF THE SAMPLE.
616
END
620

FIG. 6

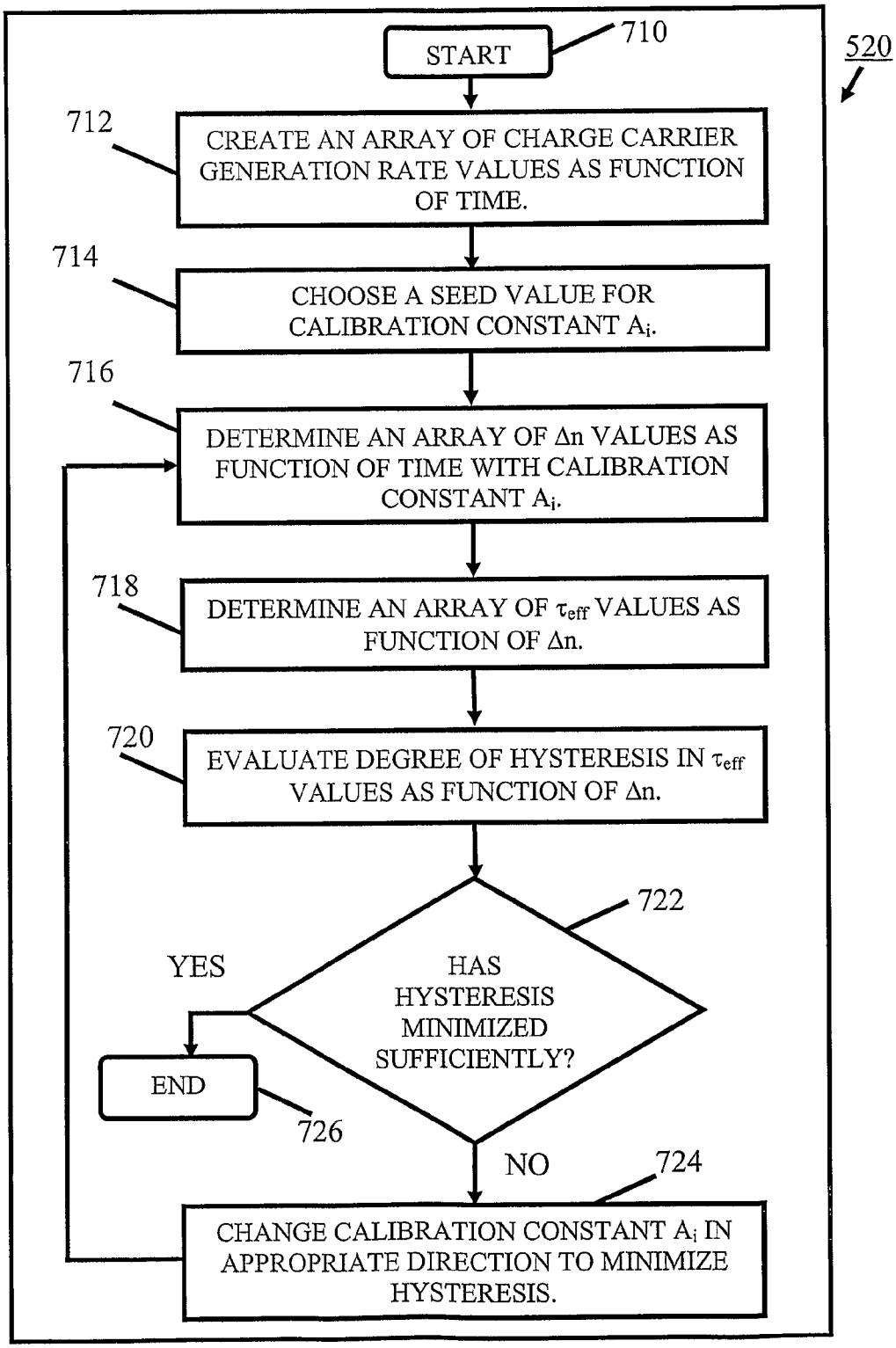

520
START
710
712
CREATE AN ARRAY OF CHARGE CARRIER GENERATION RATE VALUES AS FUNCTION OF TIME.
714
CHOOSE A SEED VALUE FOR CALIBRATION CONSTANT A_i.
716
DETERMINE AN ARRAY OF Δn VALUES AS FUNCTION OF TIME WITH CALIBRATION CONSTANT A_i.
718
DETERMINE AN ARRAY OF τ_{eff} VALUES AS FUNCTION OF Δn.
720
EVALUATE DEGREE OF HYSTERESIS IN τ_{eff} VALUES AS FUNCTION OF Δn.
722
HAS HYSTERESIS MINIMIZED SUFFICIENTLY?
YES
END
726
NO
724
CHANGE CALIBRATION CONSTANT A_i IN APPROPRIATE DIRECTION TO MINIMIZE HYSTERESIS.

FIG. 7

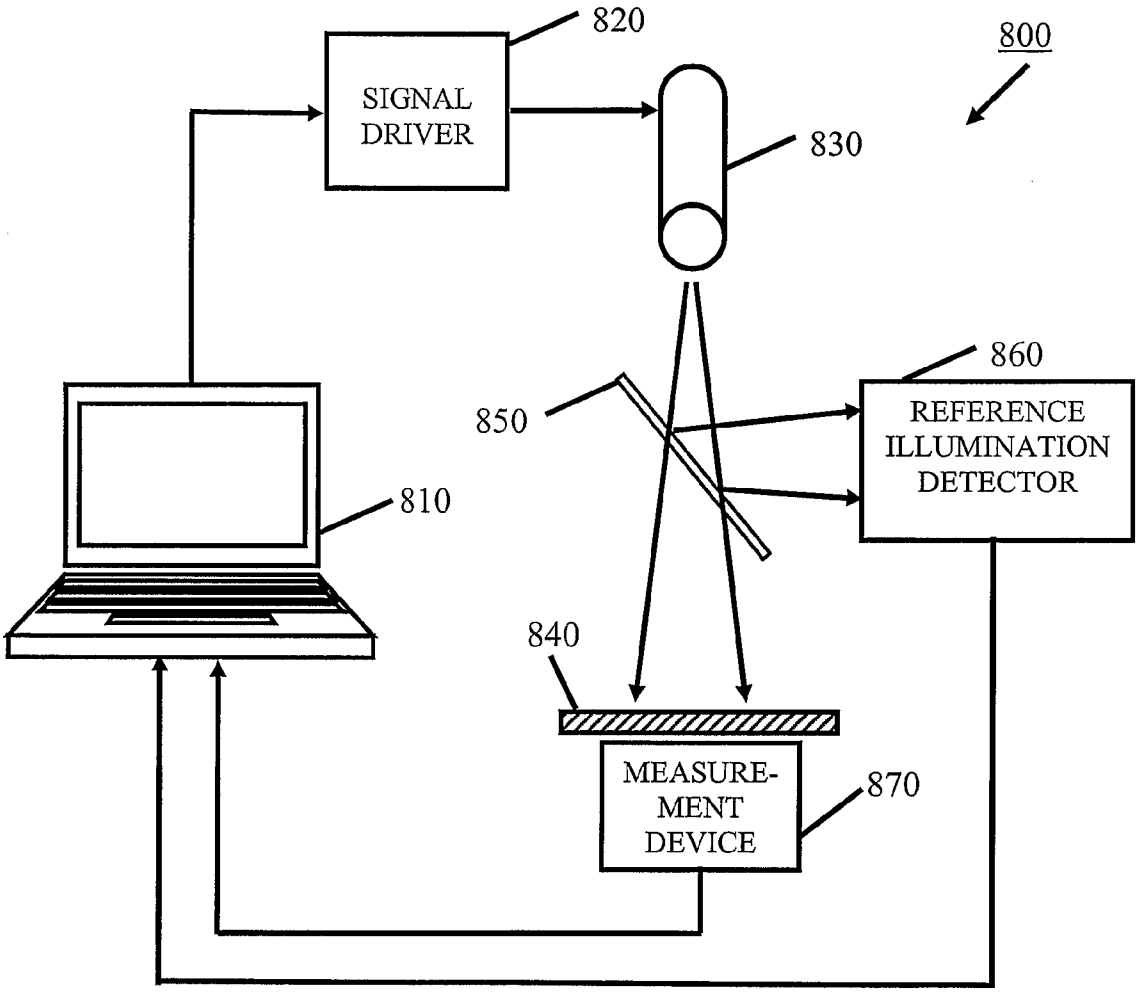

820
800
SIGNAL DRIVER
830
860
850
REFERENCE ILLUMINATION DETECTOR
810
840
MEASURE-MENT DEVICE
870

FIG. 8

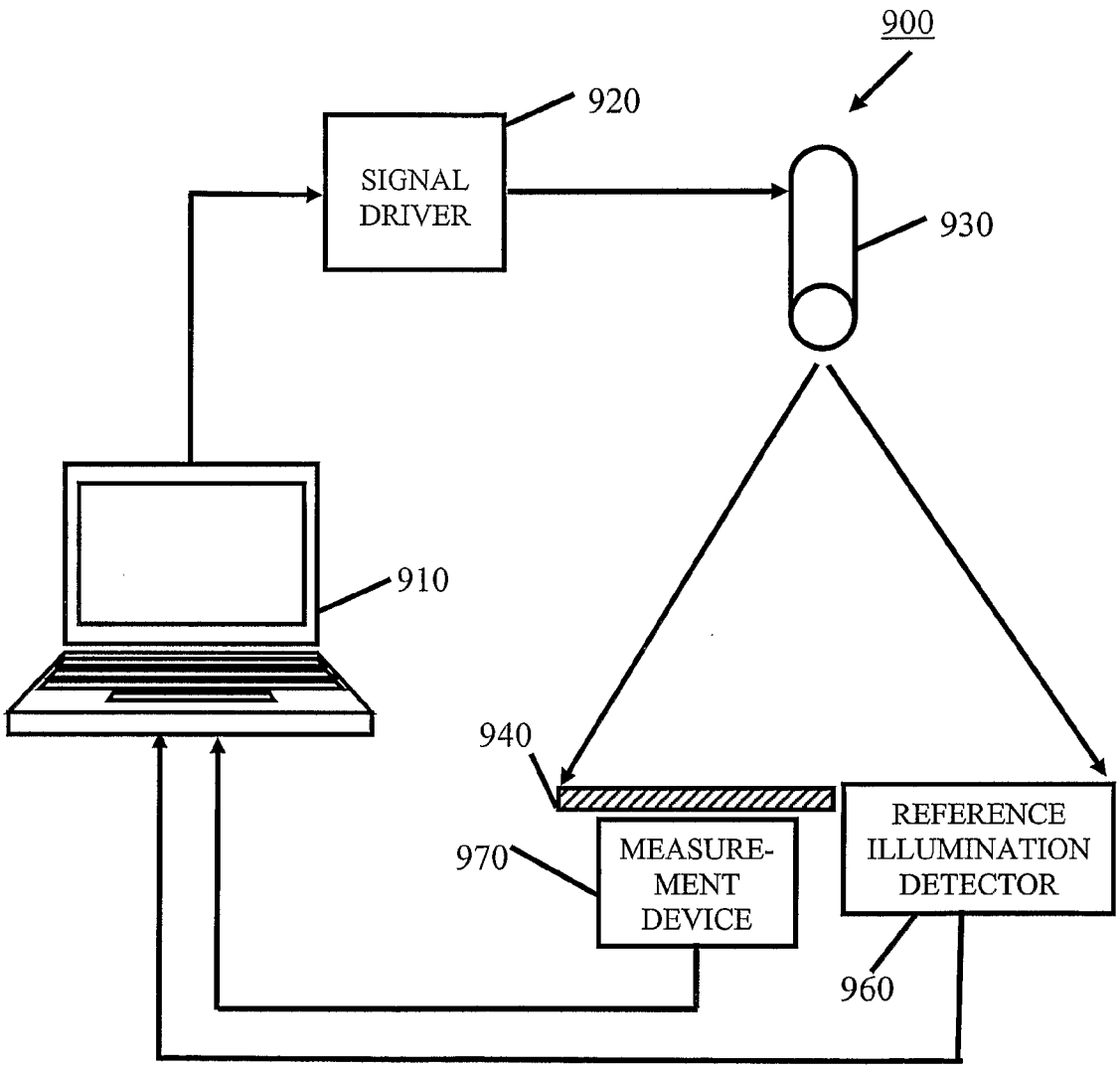

900
920
SIGNAL DRIVER
930
910
940
970
MEASURE-MENT DEVICE
REFERENCE ILLUMINATION DETECTOR
960

FIG. 9

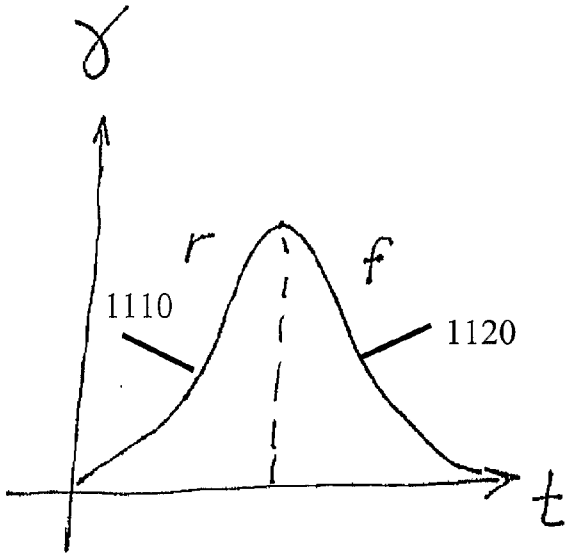


FIG. 11

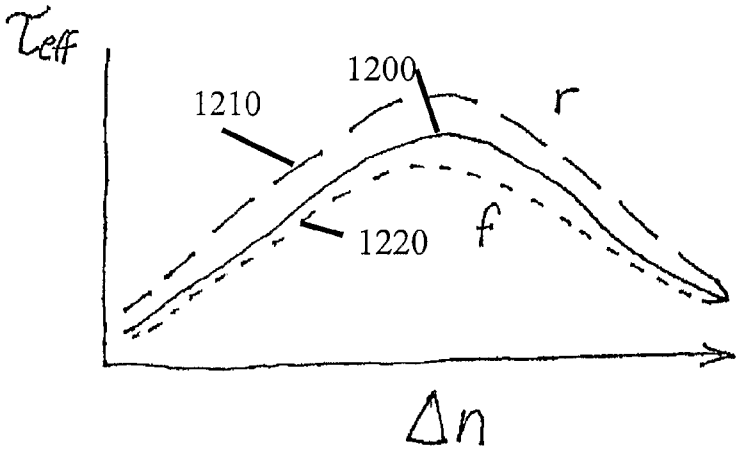


FIG. 12

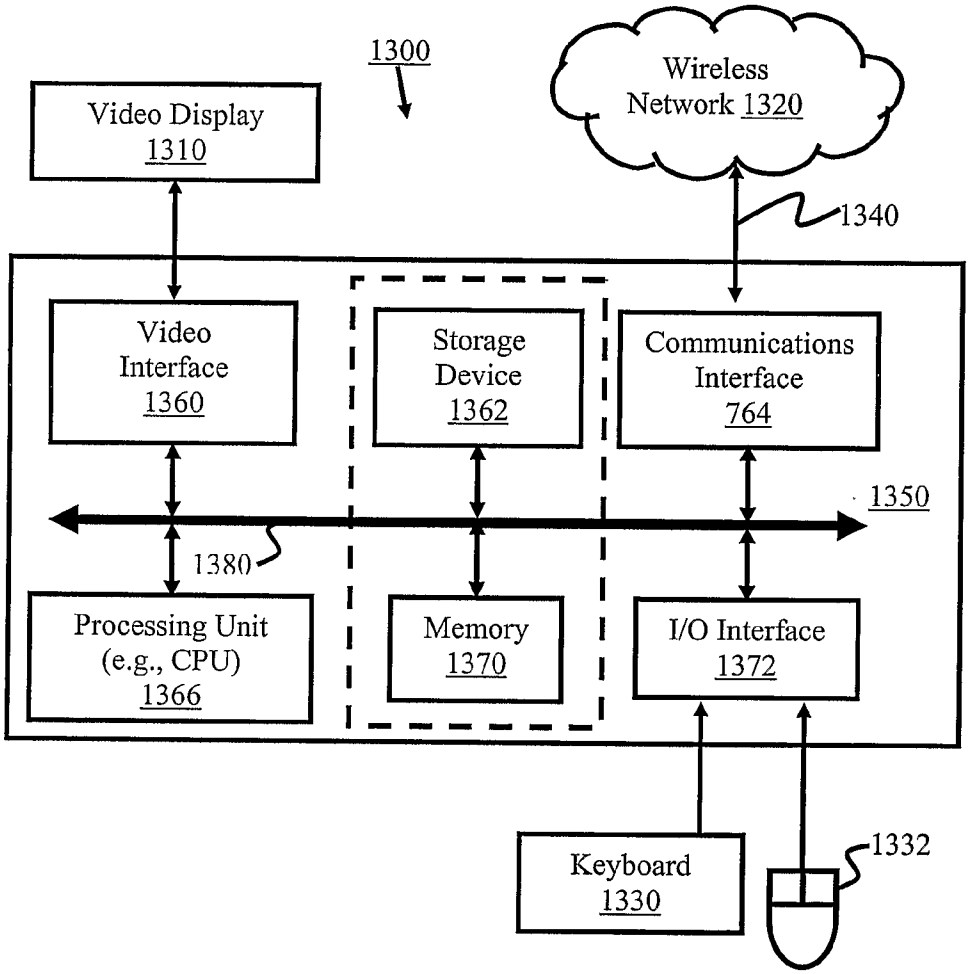

1300
Wireless Network 1320
Video Display 1310
1340
Video Interface 1360
Storage Device 1362
Communications Interface 764
1350
1380
Processing Unit (e.g., CPU) 1366
Memory 1370
I/O Interface 1372
Keyboard 1330
1332

FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2006/001625

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G01R 31/26 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT, EPPATENTS, EPAPAT, EPBPAT, USAPPS, USPAT. KEYWORDS: CHARGE, CARRIER, PHOTOLUMINESCENCE, PHOTO CONDUCTANCE, CALIBRATE, SEMICONDUCTOR AND SIMILAR.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/0075460 A1 (HOWLAND) 22 April 2004 Whole document.	1 to 70
A	US 2002/0167326 A1 (BORDEN et al) 14 November 2002 Whole document.	1 to 70
A	CA 2126481 (MANDELIS et al) 23 December 1995 Whole document.	1 to 70
A	US 4661770 A (von ROOS) 28 April 1987 Whole document.	1 to 70

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
03 January 2007	8 JAN 2007
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized officer **RICHARD REED** Telephone No : (02) 6283 7927

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU2006/001625

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	2004075460	EP	1413892	JP	2004146831	US	6836139
US	2002167326	US	6812717	US	7130055	US	2005088187
CA	2126481	US	5667300				
US	4661770						

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX